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PB89-161061

THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES

DRAFT

REPORT TO CONGRESS

Volume 2: National Studies

United States Environmental Protection Agency
Office of Policy, Planning, and Evaluation
Office of Research and Development

October, 1988

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Editors: Joel B. Smith and Dennis A. Tirpak

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CHAPTER 8

WATER RESOURCES

FINDINGS

Many regions of the country are likely to experience changes in water availability and water quality. The frequency of droughts and floods may change. Under some scenarios, summer soil moisture and water availability in middle latitudes may be reduced due to temperature increase, a northward shift of the rainbelt, and an earlier onset of winter snowbelt and spring runoff. Even under warm-wet scenarios, in many regions the positive effect on supply of increased precipitation may be more than offset by temperature increases that reduce supply by evaporation and increase water demand.

- A warmer and drier climate in some regions would decrease water supplies and increase water demand, especially demand for irrigation and electric power production.

- Lower river flows resulting from drier conditions could negatively affect hydropower production, navigation, aquatic ecosystems, wildlife habitat, and recreation.

- Lower stream flow and lower lake levels could cause power plants to locate in coastal areas to obtain a water source that is reliable and that may be used without violation of thermal restrictions. This would have important implications for land use, transmission lines, and the costs of power.

- Municipal and industrial water users may have greater incentives to purchase water rights in the West to ensure the reliability and quality of supply.

- Because of earlier runoff and potentially higher evaporation, increased rainfall may not increase water availability in all regions. However, flooding may increase. Flood-prone regions may require structural modifications, new capital improvements, and modifications in operating rules for reservoirs.

Policy Implications

- Changes in water availability and water quality and conflicts among water users are the major impacts of climate change on water resources, although the magnitude and distribution of hydrologic and water resource effects are still uncertain. Responses could include the following:

- -- build new storage capacity, provided that the structures show positive net benefits under a variety of possible climatic conditions;
- -- modify water system operations to improve performance under extreme conditions, to enhance recovery from extreme conditions, and to accept greater risk to low-valued uses in order to protect high-valued uses; and
- -- encourage a reduction in water demand and an increase in water use efficiency through conservation, water markets, water quality control, contingency planning, and coordinated uses of regional and interstate water resources, provided that such measures do not reduce the performance and recovery capabilities of supply systems.

CLIMATE, HYDROLOGY, AND WATER RESOURCES IN THE UNITED STATES

The United States is endowed with a bountiful supply of water, but the water is not always in the right place at the right time or of the right quality.

On the average, 4,200 billion gallons per day (bgd) of precipitation fall on the lower 48 States. However, a large portion of this water evaporates, leaving only 1,435 bgd to run off into surface water and groundwater.

Surface and groundwaters are managed by controlling and diverting flows through impoundments and aqueducts; by withdrawing water for such "off-stream" uses as irrigation and municipal use; by regulating flows to maintain "in-stream" water quality and such uses as navigation, hydropower, and recreation, and by controlling flows under flood conditions to avoid loss of life, damage to property, or inconvenience to the public. Water may be "withdrawn" and returned to the source more than once, or "consumed" and not returned to the source.

Control and use of water are costly. Water supply for municipal and industrial use represented a $108 billion national investment in infrastructure in 1984 (National Council on Public Works Improvement, 1988). Government agencies and industries spent $336 billion (in constant 1982 dollars) from 1972 to 1985 (Farber and Rutledge, 1987) on water pollution abatement and control activities. In other areas, excess water periodically floods agricultural and urban areas, causing an average of $3 billion (in constant 1984 dollars) (National Council on Public Works Improvement. 1988) per year in damages during the past decade.

Most water resource decisions in the past have been based on the assumption that the climate of a region varies around a stationary mean. Even without climate change, the ability to use water resources is greatly influenced by weather variability. As shown in Figure 8-1, weather controls hydrologic conditions through precipitation (mean and frequency), runoff, snowmelt, transpiration and evaporation, soil moisture, and the variability of storms and drought.

Water Availability

On a national scale, water supplies are adequate. Largely due to weather variability, only 675 bgd of the 1,435 bgd of runoff water in the conterminous United States is considered available in 95 out of 100 years for irrigation, municipal, industrial, and other off-stream uses. In 1985, freshwater withdrawals for off-stream uses were 338 bgd. Ninety-two bgd of the withdrawals were consumed, mostly for irrigation.

The supply of water from surface and groundwater sources for soil moisture, in-stream uses, withdrawal, and consumption is vulnerable to decreased precipitation. Warmer temperatures would increase the proportion of rain versus snow, would cause earlier runoff of winter snowpacks, and would increase evaporation. These effects would diminish water availability during the summer and reduce water levels and flows.

Although water availability exceeds withdrawals and consumption, the water is not always in the right place at the right time. In some regions, the gap between demand for water and available supply is narrow. For example, average surface water withdrawal exceeds average streamflow in the Great Basin, Rio Grande, and Colorado River Basins. In these water-short basins, off-stream water uses often conflict with in-stream uses, such as recreation and maintenance of environmental quality. Degraded water quality further limits water availability in many regions.

Water Uses

The uses primarily affected by water availability constraints are irrigation, thermoelectric power, and industrial and domestic water use. Withdrawals and consumption of freshwater by major offstream uses in 1985 are summarized in

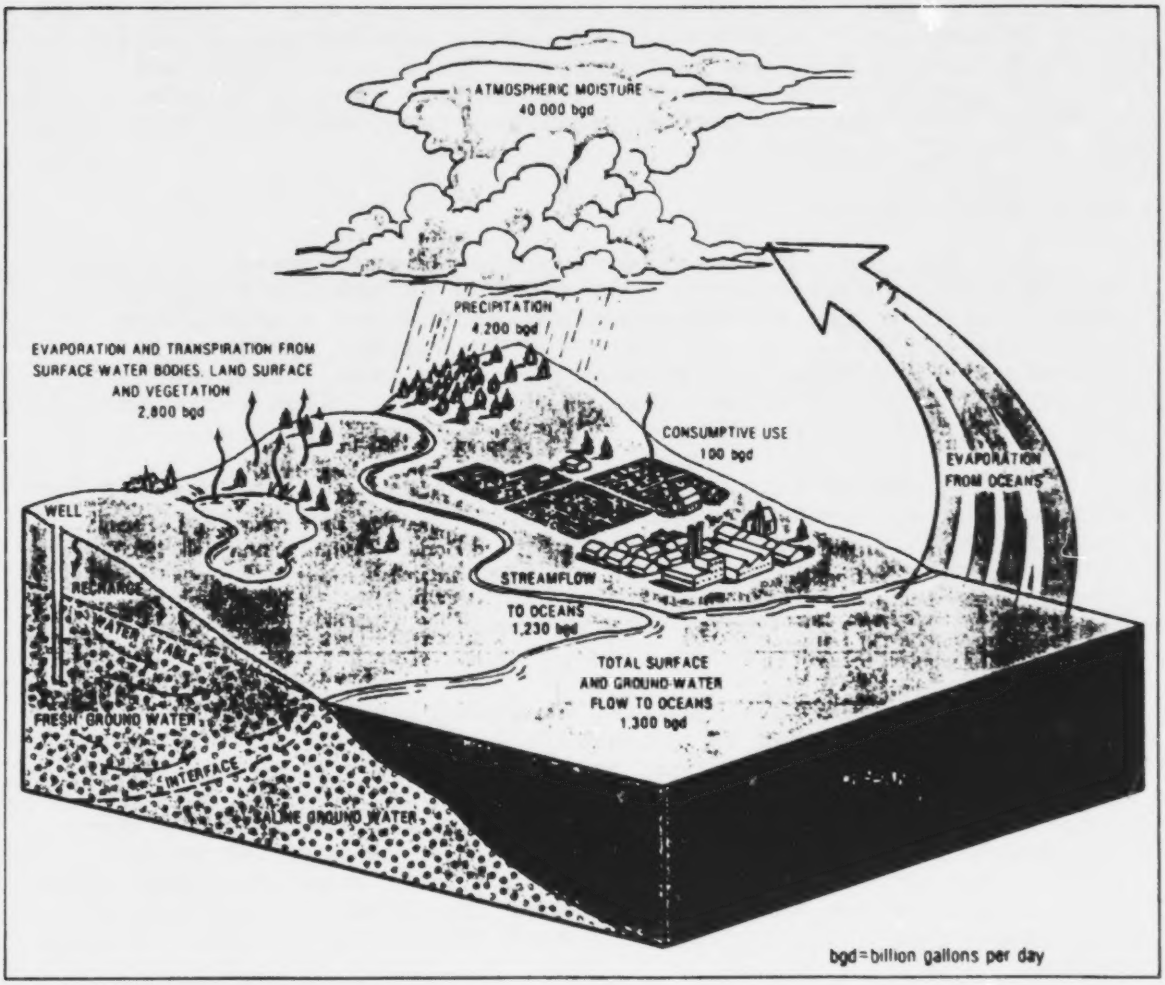
ATMOSPHERIC MOISTURE 40 000 bgd
PRECIPITATION 4,200 bgd
EVAPORATION AND TRANSPIRATION FROM SURFACE WATER BODIES, LAND SURFACE AND VEGETATION 2,800 bgd
CONSUMPTIVE USE 100 bgd
EVAPORATION FROM OCEANS
WELL
RECHARGE
WATER TABLE
STREAMFLOW TO OCEANS 1,230 bgd
TOTAL SURFACE AND GROUND-WATER FLOW TO OCEANS 1,300 bgd
FRESH GROUND WATER
INTERFACE
SALINE GROUND WATER
bgd=billion gallons per day

Figure 8-1. Hydrologic cycle showing the gross water budget of the conterminous United States.

Source: Langbein et al. (1949) and Solley et al. (1983).

As the largest and relatively least valuable use of freshwater, irrigation accounts for 42% of freshwater withdrawals and 82% of fresh water consumption in the United States. Although irrigated land comprises about 10% of harvested cropland acreage nationwide, it contributes 30% of the value of cropland production. Many of these crops are fruits, vegetables, and specialty crops (U.S. Water Resources Council, 1978; Bajwa et al., 1987). The 17 Western states account for 85% of the irrigated lands in the country (Bajwa et al., 1987).

In contrast, thermoelectric powerplants withdraw almost as much freshwater as irrigation but consume much less than irrigation. Although 131 bgd of freshwater are withdrawn to produce 60% of the nation's electricity (Water Resources Council, 1978), only 4.35 bgd are actually consumed (Solley et al., 1988).

Domestic uses account for 10% of total water withdrawn and 11% of consumption. Over the past 20 years, domestic water use has increased from 16 to 25 bgd owing to growth in the number of households, with little change in usage per household (Solley et al., 1988).

Water Quality

Degraded water quality reduces the amount of water for human use. The Nation has made significant progress in cleaning up water pollution since the enactment of the 1972 Clean Water Act. However, some of the States reported that some persistent pollution problems remain, especially contamination by toxic pollutants and nonpoint source pollution (USEPA, 1987b). Water quality in the nation's rivers, lakes, and streams depends in part on water quantity. Water supply is needed for dilution of wastewaters that flow into surface and groundwater sources. Freshwater inflows are needed to repel saline waters in estuaries and to regulate water temperatures in order to forestall changes in the thermal stratification, water quality, aquatic biota, and ecosystems of lakes, streams, and rivers.

Flood Control

Major water management systems and structures, which are designed to reduce hazards and damages from major floods, may have the flexibility to adapt to modified flood conditions. The major concern with existing dams and levees is the consequence of failure under extreme conditions.

For instance, an increased probability of great floods, whether due to urbanization of upstream watersheds or climate

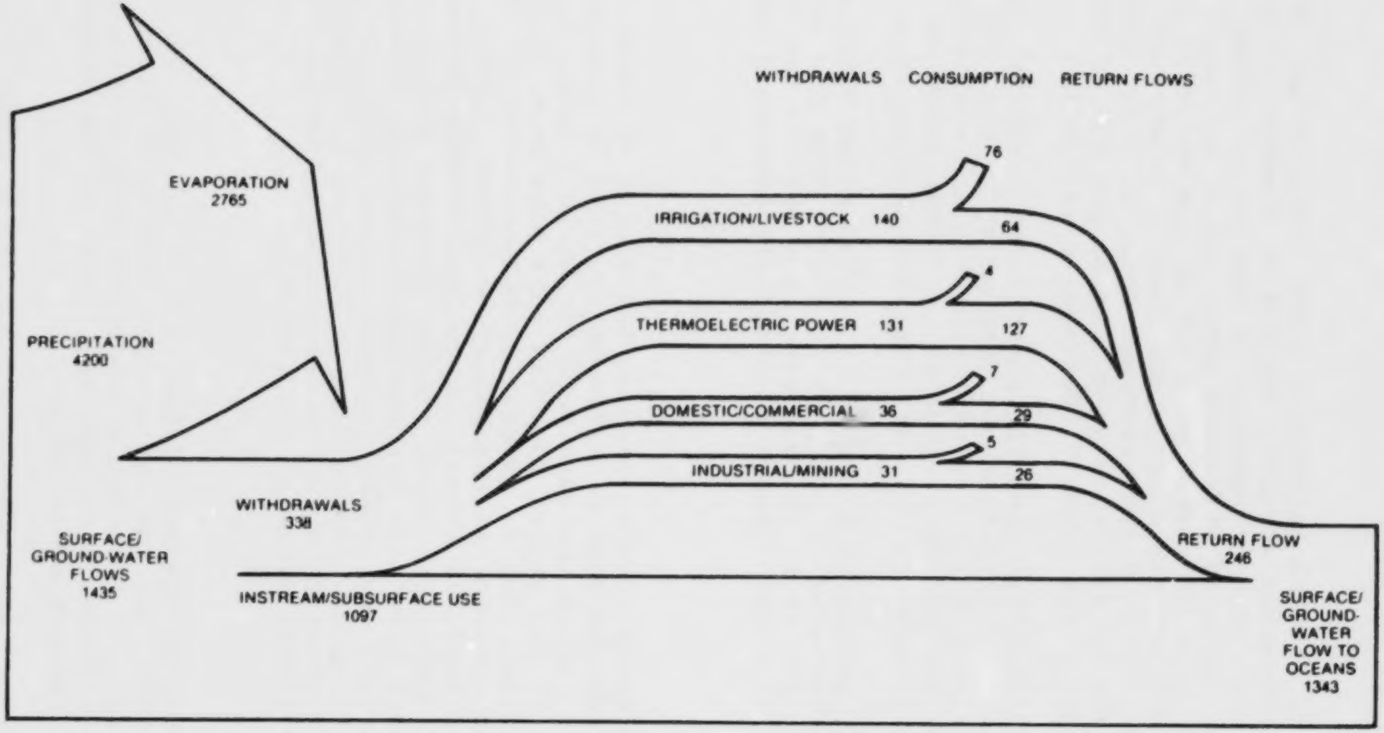
WITHDRAWALS
CONSUMPTION
RETURN FLOWS
EVAPORATION 2765
PRECIPITATION 4200
SURFACE/ GROUND-WATER FLOWS 1435
WITHDRAWALS 338
INSTREAM/SUBSURFACE USE 1097
IRRIGATION/LIVESTOCK 140
76
64
THERMOELECTRIC POWER 131
4
127
DOMESTIC/COMMERCIAL 36
7
29
INDUSTRIAL/MINING 31
5
26
RETURN FLOW 246
SURFACE/ GROUND-WATER FLOW TO OCEANS 1343

Figure 8-2. Water withdrawals and consumption by offstream uses, coterminous United States, 1985. Source: Solley et al. (1988).

change, would cause dams with inadequate spillways to fail. Some major structures may be currently vulnerable to a "probable maximum flood" (National Research Council, 1986). Smaller structures, such as urban drainage culverts and sewers and local flood protection projects, are currently more susceptible to floods and are in poorer condition than large structures (National Council on Public Works Improvement, 1988).

REGIONAL IMPACTS OF CLIMATE CHANGE

The EPA regional studies reported in this document use scenarios generated from up to four GCMs as their starting points (see Chapter 3) and match them with regional water resource models. This section combines the results from this report's EPA studies on California, the Great Plains, the Great Lakes, and the Southeast with previous studies of the impacts of climate change on these and other regions. The EPA studies are listed in Table 8-1.

Climate impacts may be greatest on regions already stressed: where water demand is great and supply is short, where water quality has deteriorated, or where periodic excess supply floods agricultural and urban lands. Table 8-2 summarizes the current status of water supply by major river basin region. The regions are delineated in Figure 8-3.

West

The arid and semiarid river basins west of the Mississippi show up as problem areas in all four of the U.S. Water Resources Council's water quantity and quality maps. Total water use exceeds average streamflow in 24 of 53 western water resource regions (U.S. Water Resources Council, 1978). The majority of the West's water withdrawals go to irrigation. Surface and groundwater quality in the West have deteriorated due to low flow, salts concentrated by irrigation, and pesticide use. The West also depends upon nonrenewable groundwater supplies for irrigation (Solley et al., 1988).

Climate change may exacerbate water shortage and quality problems in the West. Some GCM scenarios predict midsummer drought and heat, less groundwater recharge, and less groundwater and surface water available for irrigation in the middle latitudes of the country. The sensitivity analyses conducted by Stockton and Boggess (1979) indicated that the warmer and drier

Table 8-1. Water Resource Studies

Region	Study
California	o Interpretation of Hydrologic Effects of Climate Change in the Sacramento-San Joaquin River Basin, California - Lettenmaier, University of Washington.
	o Methods for Evaluating the Potential Impact of Global Climate Change - Sheer and Randall, Water Resources Management, Inc.
	o The Impacts of Climate Change on the Salinity of San Francisco Bay - Williams, Philip Williams & Associates
Great Lakes	o Effects of Climate Changes on the Laurentian Great Lakes Levels - Croley, Great Lakes Environment Research Lab.
	o Impact of Global Warming on Great Lakes Ice Cycles - Assel, Great Lakes Environment Research Lab.
	o The Effects of Climate Warming on Lake Erie Water Quality - Blumberg and DiToro, HydroQual, Inc.
	o Potential Climatic Changes to the Lake Michigan Thermal Structure - McCormick, Great Lakes Environment Research Lab.
Great Plains	o Effects of Projected CO_2 - Induced Climate Changes on Irrigation Water Requirements in the Great Plain States - Allen and Gichuki, Utah State University.
Southeast	o Potential Impacts of Climatic Change on the Tennessee Valley Authority Reservoir System - Miller and Brock, Tennessee Valley Authority.

Chapter 8

- Impacts on Runoff in the Upper Chattahoochee River Basin - Hains, C.F. Hydrologist, Inc.
- Methods for Evaluating the Potential Impact of Global Climate Change - Sheer and Randall, Water Resources Management, Inc.

Table 8-2. Current Status of Water Supply

Water-Resources Region	Average Renewable Supply in billion gallons per day	1985 Withdrawals as a percentage of Average Renewable Supply	1985 Consumption as a percentage of Average Renewable Supply	Reservoir Storage as a percentage of Average Renewable Supply	Streamflow Exceeded 95% of time as a percentage of Average Streamflow	Percentage of Groundwater Overdraft
New England	78.4	11.7	9	15	62.4	0
Mid-Atlantic	80.7	29.5	21	11	62.2	1.2
South Atlantic-Gulf	233.5	13.5	21	15	55.5	6.2
Great Lakes	74.3	42.9	29	8	62.6	2.2
Ohio (exclusive of Tennessee Region)	139.5	22.3	15	13	59.0	0
Tennessee	41.2	22.3	8	24	77.0	0
Upper Mississippi (exclusive of Missouri Region)	77.2	21.9	23	14	54.0	0
Mississippi (entire basin)	464.3	3.7	12	32	46.7	0.5
Souris-Red Rainy	6.5	4.3	19	110	32.1	0
Missouri	62.5	55.2	203	120	40.7	24.6
Arkansas-White-Red	68.6	22.3	117	41	36.5	61.7
Texas-Gulf	33.1	41.4	182	67	27.5	77.2
Rio Grande	5.1	109.8	437	182	33.3	28.1
Upper Colorado	14.7	51.4	163	229	39.0	0
Colorado (entire basin)	15.6	47.4	272	403	75.0	48.2
Great Basin	9.9	81.8	364	30	50.0	41.5
Pacific Northwest	276.2	12.9	45	20	70.7	8.5
California	70.2	53.6	299	49	44.0	11.5
Alaska	975.5	0.4	0	0.1	78.5	0
Hawaii	7.4	17.2	18	0.1	60.3	0
Caribbean	5.1	11.9	32	5	35.6	5.1

Average renewable supply is defined as the average flow potentially or theoretically available for use in the region.
Data from U.S. Water Resources Council, 1978; U.S. Geological Survey, 1983; Solley et al., 1988.

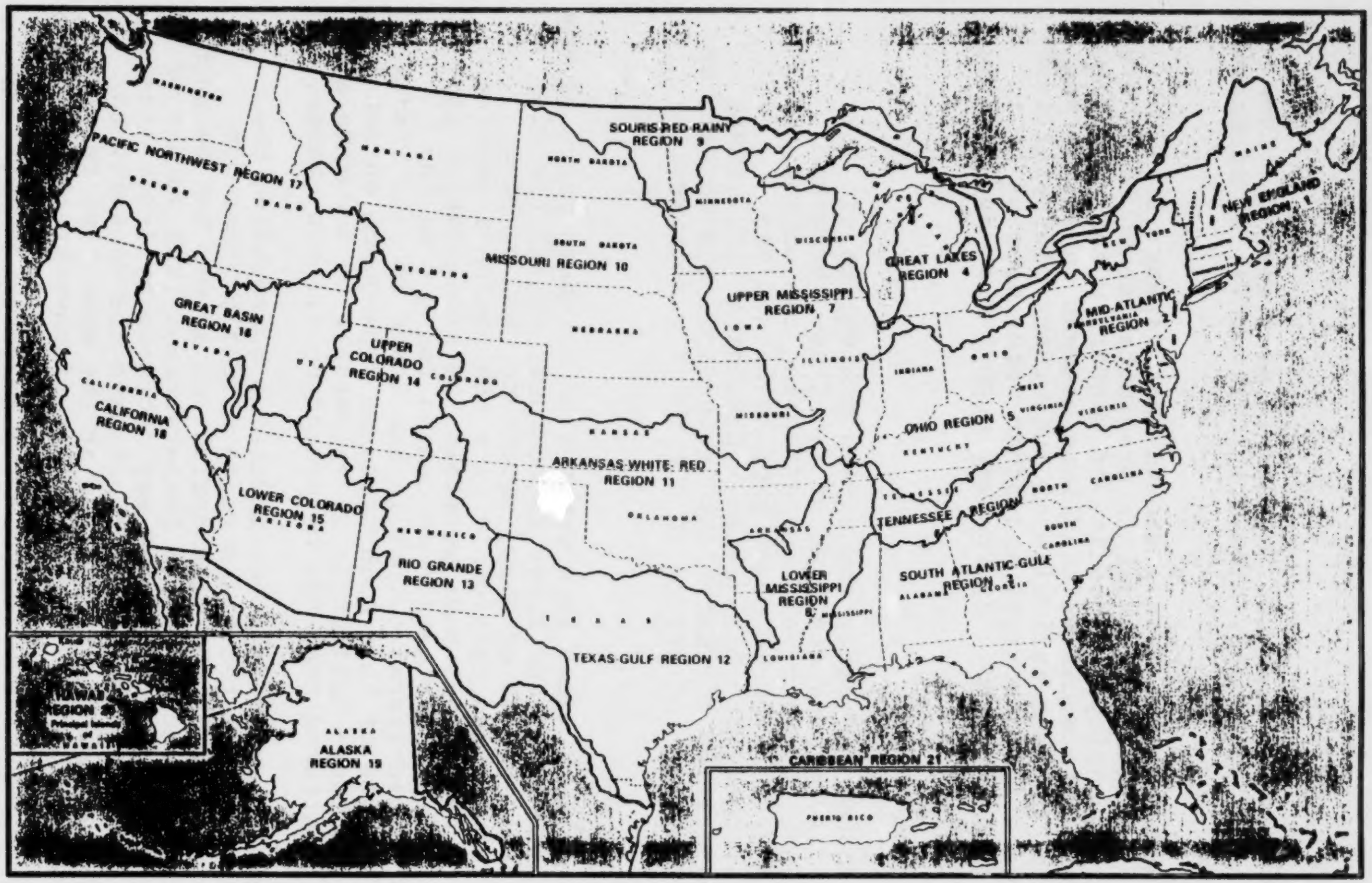
WASHINGTON
PACIFIC NORTHWEST REGION 17
OREGON
IDAHO
MONTANA
SOURIS-RED-RAINY REGION 9
NORTH DAKOTA
MINNESOTA
WISCONSIN
NEW ENGLAND REGION 1
MAINE
NEW YORK
GREAT LAKES REGION 4
SOUTH DAKOTA
MISSOURI REGION 10
WYOMING
UPPER MISSISSIPPI REGION 7
IOWA
MID-ATLANTIC REGION 2
PENNSYLVANIA
GREAT BASIN REGION 16
NEVADA
UTAH
UPPER COLORADO REGION 14
COLORADO
NEBRASKA
ILLINOIS
INDIANA
OHIO
CALIFORNIA
CALIFORNIA REGION 18
KANSAS
MISSOURI
OHIO REGION 5
WEST VIRGINIA
VIRGINIA
KENTUCKY
ARKANSAS-WHITE-RED REGION 11
OKLAHOMA
LOWER COLORADO REGION 15
ARIZONA
NEW MEXICO
TENNESSEE REGION 6
NORTH CAROLINA
SOUTH CAROLINA
ARKANSAS
RIO GRANDE REGION 13
LOWER MISSISSIPPI REGION 8
MISSISSIPPI
SOUTH ATLANTIC-GULF REGION 3
ALABAMA
GEORGIA
TEXAS
TEXAS GULF REGION 12
LOUISIANA
FLORIDA
HAWAII REGION 20
ALASKA
ALASKA REGION 19
CARIBBEAN REGION 21
PUERTO RICO

Figure 8-3. Water Resources Regions climate
Source: USGS, 1985

scenarios may have the greatest impacts in arid western river basins (Rio Grande, Colorado, Missouri, California) by increasing water shortages.

Revelle and Waggoner (1983) showed that warmer air temperatures and slight decreases in precipitation could severely reduce both the quantity and quality of western water resources. Water shortages and associated conflicts between in-stream and off-stream uses, between agricultural and urban/industrial water uses, and between flood control and other water uses of reservoirs may be expected. Hydropower output also may decline due to lower riverflow.

Pacific Northwest

Climate change may alter the timing and volume of precipitation, increasing the risk of flooding, changing reservoir management practices, and affecting the output and reliability of hydroelectric power production and the availability of water for irrigation. Butcher et al. (1986) found that competition for water for irrigation, hydropower, and fisheries habitats is increasing in the Pacific Northwest.

California

The diversion of water from water-rich northern parts of the State and from the Colorado River to southern California via Federal and State systems of dams, aqueducts, and pumping stations has transformed California into the nation's leading agricultural state and has made possible the urbanization of southern California. Irrigation accounted for 83% of the total value of agricultural output in the State in 1982 (Bajwa et al., 1987). Because of this high economic dependence on water in an arid area, southern California is vulnerable to droughts and altered runoff patterns that may be caused by climate change.

Total annual runoff from the mountains surrounding the Central Valley is estimated to increase slightly under GCM scenarios, but runoff in the late spring and summer may be much less than today because of higher temperatures. The volume of water from the State Water Project may decrease by 7-16% (see Chapter IV). Current reservoirs do not have the capacity to increase storage of winter runoff and at the same time retain flood control capabilities. In addition, freshwater requirements to repel saline water near the major freshwater pumping facilities in the upper Sacramento-San Joaquin River Delta may have to be doubled under sea level rise scenarios, further reducing water available to southern California.

Decreases in water availability due to climate change may also cut hydroelectric power produced in California. In the 1976-77 drought, hydroelectric production in northern California dropped to less than 50% of normal, a deficiency relieved by importing surplus power from the Pacific Northwest and by burning additional fossil fuels at an approximate cost of a half billion dollars (Gleick, 1988).

Colorado, Rio Grande, and Great Basin River Basins

Total consumption is more than 40% of renewable supply in these river basins. The Colorado River Basin has huge reservoir storage, but demand exceeds supply in the lower half of the basin.

Ordinarily all of the Colorado River's water is consumed before it reaches the Gulf of California in Mexico. The Colorado River Compact of 1922, the 1963 Supreme Court decision in Arizona v. California, 1944 and 1973 treaties with Mexico, and other agreements define the allocation of Colorado River water to seven States and Mexico (Dracup, 1977). Some studies show that the Upper Colorado region will use all of its allocation by the year 2000, curtailing water available to lower Colorado and California (Kneese and Bonem, 1986). Climate change may further reduce the availability of water in these basins. Stockton and Boggess's (1979) model of a 2°C temperature increase and a 10% precipitation decrease cuts water supply in the upper Colorado by 40% and in the Rio Grande by 76%. Flaschka (1984) found that a decrease in precipitation of 25% combined with a temperature increase of 2°C could decrease annual runoff by 50% in the Great Basin.

Great Plains

The southern Great Plains States of Kansas, Nebraska, Oklahoma, and Texas produce almost 40% of the nation's wheat, 15% of its corn, and 50% of its fattened cattle (see Chapter 10). The region heavily depends on groundwater mining (when pumping exceeds aquifer recharge) for irrigation. The region was hard hit during the "dust bowl" years of the 1930s and suffered from severe drought in 1988 (see Chapter 10).

Because of greater stability in irrigated yields relative to dryland yields, a rise in commodity prices will make expansion of irrigated production economically feasible. Thus, while total agricultural acreage is expected to decrease, irrigated acreage and groundwater mining are expected to increase in the southern Great Plains (Chapter 10). Greater demand may be placed on the

Ogallala Aquifer, which underlies much of the region, causing further groundwater mining of the aquifer.

Water quality appears to be vulnerable to deterioration because of increased use of agricultural pesticides as a response to climate change in surface runoff and erosion and decreased water flows.

Great Lakes

According to the GCMs, higher temperatures may overwhelm any increase in precipitation and may evaporate lakes to below the lowest levels on record. The winter ice cover would be reduced but would still be present, especially in shallow areas and northern lakes. Navigation depths, recreation, erosion (e.g., shrinking Chicago shoreline), hydropower output, and water quality all would be affected (see Chapter 5).

Mississippi River

The Mississippi River has historically been affected by both spring floods and drought. In 1988, low flows due to drought received national attention. Low flows disrupt navigation, degrade the drinking water for southern Louisiana cities, and reduce the inflow of water to the vast Mississippi Delta.

Northeast

During periodic droughts in the Northeast, such as in 1962-65 and 1980-81, in-stream flow regulations ration water and threaten shutdowns of electrical powerplants (U.S. Army Corps of Engineers, 1977; Schwartz, 1977; Kaplan et al., 1981). Although the Northeast is humid, cities and powerplants demand large amounts of water at localized points in a watershed, necessitating storage and interbasin transfers. No new major storage has been built in the Northeast during the past 20 years, except the Bloomington Dam on the Potomac River. Water supply in lower New England, New York, and Pennsylvania, and power production in the Northeast remain vulnerable to the droughts that may occur, according to some climate change scenarios (Schwartz, 1977; Kaplan et al., 1981; and see Chapter 15).

Southeast

The drought of recent years is increasing demands for irrigation in the Southeast and is prompting farmers to consider shifting crops. However, studies for this report are unclear on whether the Southeast may become wetter or dryer.

Most reservoirs in the area have sufficient capacity to retain flood surges and maintain navigation, hydropower, water supply, and in-stream uses (e.g. dilution, wildlife) in both wet and dry climate change scenarios (see Chapter 6). However, dryer conditions would pose conflicts between recreational uses (which would be hurt by changes in reservoir levels) and all other in-stream and off-stream uses.

Finally, a possible decline in the flow of freshwater to the Gulf coast and estuaries would change the estuarine ecology.

NATIONAL IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

Climate change and regional models do not yet provide reliable data to indicate the net national or regional costs and benefits of climate change. Accurate quantitative predictions, such as dollar losses or numbers of people affected by climate change, cannot be made. With current information, however, we can indicate possible directions of impacts and sectors affected. For example, water shortages may stifle economic growth, impose hardships on existing users, and result in transfers of water to uses with the highest value.

A major national impact of climate change on water resources may be to increase conflicts between regional water uses. Decreased water availability and increased water demands may intensify conflicts in the following areas:

- between in-stream and off-stream uses;
- among off-stream uses, such as agriculture, domestic use, and thermoelectric power;
- between water supply and flood control in the West;
- between all uses and recreation in the Southeast; and
- between thermoelectric power production and in-stream uses, especially in the East.

Increased precipitation due to climate change may decrease conflicts in some areas, but only after management infrastructure is modified to account for large maximum floods.

The potential effects of climate change on supply and demand must be compared to existing water supply and demand and to projections for supply and demand without climate change. Figure

Most reservoirs in the area have sufficient capacity to retain flood surges and maintain navigation, hydropower, water supply, and in-stream uses (e.g. dilution, wildlife) in both wet and dry climate change scenarios (see Chapter 6). However, dryer conditions would pose conflicts between recreational uses (which would be hurt by changes in reservoir levels) and all other in-stream and off-stream uses.

Finally, a possible decline in the flow of freshwater to the Gulf coast and estuaries would change the estuarine ecology.

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8-4 outlines the national impacts of climate change on water supply and demand. Table 8-3 highlights the vulnerability of major water uses to climate change impacts by region. The following sections outline the potential impacts of climate change on traditional categories of off-stream and in-stream water uses.

Off-Stream Uses of Water Resources

Water supply and use have changed significantly during the past decade. For the first time since 1950, when the United States Geological Survey began recording water withdrawals, there was a 10% national drop in total fresh and saline water withdrawals from 1980 to 1985 (443 billion gallons to 399 billion gallons) (Solley et al., 1988). Increased conservation and water recycling in agriculture, industry, and energy production, slower growth in energy demand, and decline in availability of new water supply reduced or tempered water use in all sectors (Solley et al., 1988). Withdrawals declined by 7% in irrigation, by 33% in industry, and by 13% in thermoelectric power during the period. Of the major users, only municipal/domestic water supply increased (by 7%).

Irrigation

Water-short western States are intensively exploring avenues for minimizing water requirements. Because of depleted groundwater supplies, the rising cost of obtaining groundwater, and high costs and limited sites for new surface water developments, irrigated agriculture is no longer expanding or is declining in some areas of the West (Solley et al., 1988). Groundwater pumping for irrigation has already started to decline in the southern Great Plains States and in Arizona, although the impacts on production have been mitigated by the adoption of more efficient irrigation systems and switching to crops offering higher returns to water (Frederick and Kneese, 1988).

In contrast, supplemental irrigation in the East is on the rise (Viessman and DeMoncada, 1980). But overall, in the absence of climate change, agricultural water use trends will be characterized by only moderate increases or, in some cases, decreases in the next 20 years (Viessman and DeMoncada, 1980). Most analysts predict greater agricultural output per unit of water input.

Climate change may severely affect agriculture. Summer drought in the West and Midwest and earlier runoff are likely to

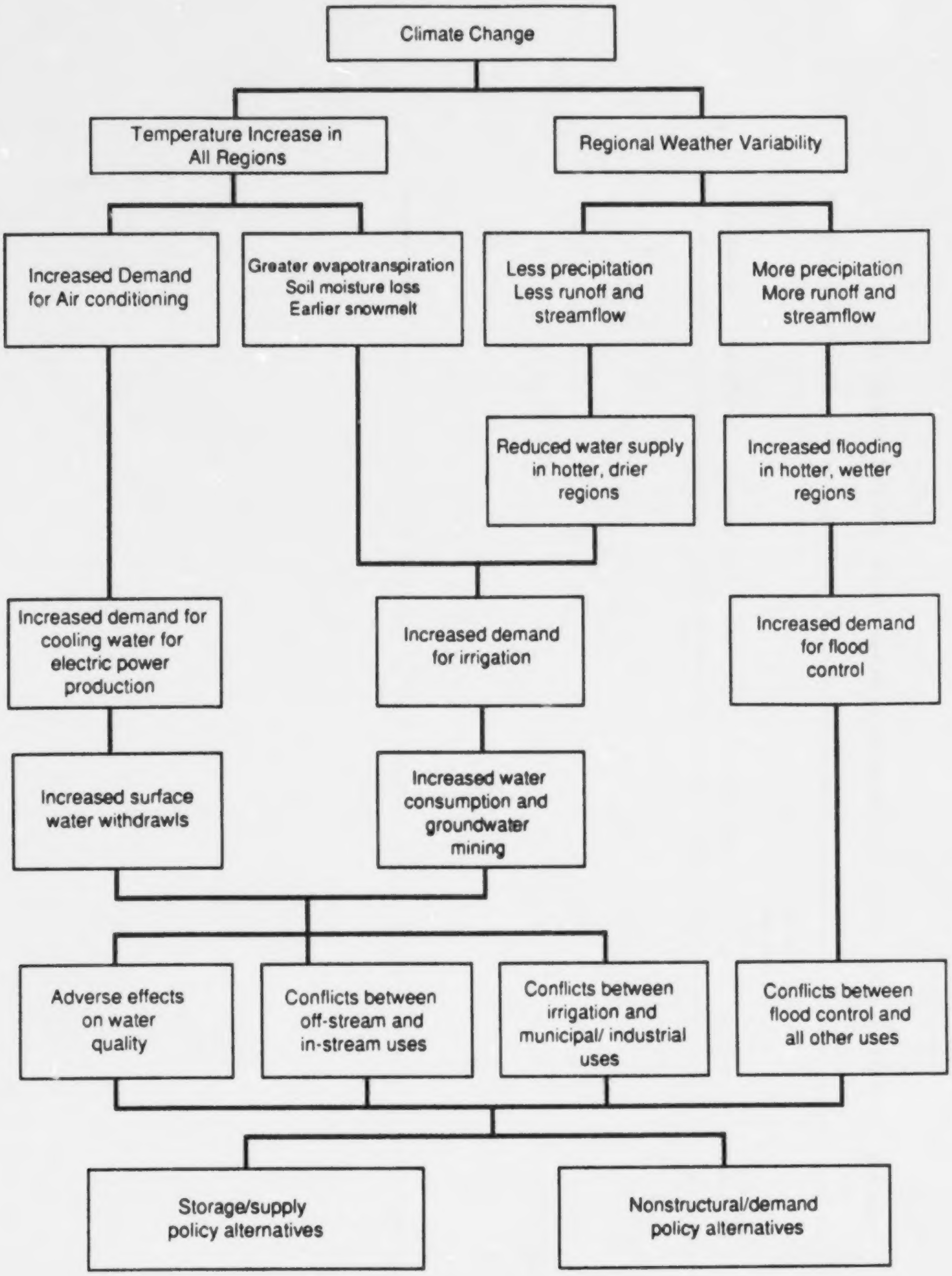
Climate Change
Temperature Increase in All Regions
Regional Weather Variability
Increased Demand for Air conditioning
Greater evapotranspiration Soil moisture loss Earlier snowmelt
Less precipitation Less runoff and streamflow
More precipitation More runoff and streamflow
Reduced water supply in hotter, drier regions
Increased flooding in hotter, wetter regions
Increased demand for cooling water for electric power production
Increased demand for irrigation
Increased demand for flood control
Increased surface water withdrawls
Increased water consumption and groundwater mining
Adverse effects on water quality
Conflicts between off-stream and in-stream uses
Conflicts between irrigation and municipal/ industrial uses
Conflicts between flood control and all other uses
Storage/supply policy alternatives
Nonstructural/demand policy alternatives

Figure 8-4. National impacts of climate change on water supply and demand.

Table 8-3. Potentail Regional Impacts of Climate Change on Water Uses: Areas of Vulnerability

	Pacific Northwest	California	Arid Western River Basins	Great Plains	Great Lakes	Mississippi	Southeast	Northeast
Irrigation	X	X	X	X			X	
Thermoelectric Power							X	X
Industrial		X	X					X
Municipal/ Domestic		X	X					X
Water Quality		X	X	X	X	X	X	X
Navigation					X	X	X	
Flood Control	X	X		X		X	X	
Hydropower	X	X			X		X	
Recreation					X		X	

change agricultural practices, cause dislocations in entire regions, and increase demands for irrigation. And even if the Southeast is wetter, higher temperatures may increase irrigation demand there (see Chapter 6).

Thermoelectric Power Generation

Future demand for water for power production will depend upon energy demand and Federal and State regulations governing in-stream water quality and thermal pollution. Due to minimum in-stream flow and maximum river temperature requirements of environmental regulations and the large amount of installed capacity along eastern rivers, freshwater withdrawals by steam electric powerplants have decreased, and siting of plants in coastal areas has increased. Thirty percent of installed capacity used saline surface water in coastal areas in 1985 (Solley et al., 1988). In addition, thermal regulations have effected a shift in new construction of cooling systems, from once-through to evaporative cooling (Miller, 1988). With once-through cooling, waste heat is discharged directly into the waste stream. Although evaporative cooling with towers and ponds alleviates thermal pollution, it increases water consumption.

During droughts, federal and state regulations protecting in-stream uses and limiting thermal discharges may constrain withdrawals for powerplant cooling (Kaplan et al., 1981; Miller, 1988). In addition, powerplant water needs on some eastern rivers are so large that during low-flow conditions, insufficient water is available to dissipate heat (Kaplan et al., 1981).

Demand for power may increase as warmer temperatures raise air-conditioning use (see Chapter 16). If streamflows are reduced as a result of climate change, powerplants using once-through cooling could be adversely affected (Miller, 1988). Increased demand for power may reinforce existing trends in powerplant design toward evaporative cooling and powerplant siting toward coastal sites. Purchases of water rights from other users by electric utilities in the West to meet cooling needs may increase. With less water available, low-flow conditions may interrupt power production and may increase power production costs and consumer electricity prices.

Industry

Since 1954, most major self-supplied industries steadily used less and less water per unit of production (Solley et al., 1988). This decline was partly due to efficiencies achieved by complying with federal and state water pollution legislation that restricts the discharge of untreated water. The trend toward more efficient industrial water uses is likely to continue. Industrial production across the country may be constrained by water quality if flow drops, and production in the West may be constrained by water supply curtailment.

Domestic Water Uses

Most municipal water supply systems are designed to provide reliable water at all times (safe yield). However, urban growth depends upon developed water supply which may be rapidly exhausted in some areas. In the Southeast and parts of the West, a large percentage of municipal water supply comes from groundwater (U.S. Water Resources Council, 1978; Solley et al., 1988). These regions have few groundwater recharge programs, so drought caused by climate change may decrease groundwater quality and quantity (see Chapters 6 and 7).

As relatively high-valued users of water, municipalities in the West are purchasing water rights to ensure adequate water supplies for urban growth. In the East, Midwest, and Southeast, municipalities may be able to increase safe yield by repairing and replacing existing leaking water delivery systems and by consolidating fragmented water supply districts.

In-stream Uses and Water Quality

The value of in-stream uses has risen relative to off-stream uses. Navigation and hydropower have retained their importance, as the values of wastewater dilution, ambient water quality, fish and wildlife habitats, and recreation have risen. Higher values placed on in-stream uses have made diversion of water for such uses as agriculture in the West and for powerplant cooling, more difficult. In general, climate change may put pressures on in-stream water uses and may degrade water quality.

Water Quality

The Federal Clean Water Act and its amendments ushered in a new era of water pollution control. Massive expenditures have decreased the amount of "conventional" water pollutants entering national water supplies. Total public and private, point and non-point, capital and operating water pollution abatement and control expenditures from 1972 to 1985 totaled $336 billion in 1982 dollars (Farber and Rutledge, 1987). Nevertheless, serious water quality problems remain.

One-third of municipal sewage treatment plants have yet to comply with the provisions of the Clean Water Act (USEPA, 1987a). federal and state regulations governing previously unregulated toxic and hazardous water pollutants has just begun. And in the West, irrigation has caused the salinity levels in the water and soils in several river basins (the lower Colorado, the Rio Grande, and the San Joaquin) to rise so high that the viability of irrigation is being threatened (Frederick and Kneese, 1988).

With climate change, less freshwater may be available in some cases for diluting wastewater and recharging aquifers. Furthermore, increased thermal stratification accompanied by enhanced algal production may degrade the water quality of many lakes. Finally, the combination of declining freshwater availability and rising sea level would move salt wedges up estuaries, changing estuarine ecology and threatening municipal and industrial water supplies on the other hand, increased flows could allow for greater dilution of pollutants.

Navigation

Lower riverflow and lake levels would impede navigation. Systems that are particularly vulnerable are those with unregulated flow and high traffic, such as the lower Mississippi River and the Great Lakes.

Flood Control

The expected changes in the timing and magnitude of snowmelt and precipitation nationwide may restrict the flood control and multiple use capabilities of existing reservoirs and other structures. For example, drawing down the levels of reservoirs to contain floodwaters from anticipated increases in precipitation or earlier snowmelt may curtail water availability for other uses.

Because of the buffering and redundancy designed into large structures, major Federal flood control projects may be able to contain or mitigate the impacts of more frequent or severe floods. In addition, the majority of dams that provide substantial flood storage are in good condition. The National Dam Safety Inventory shows that the overall condition of the U.S. Army Corps of Engineers' more than 300 flood control reservoirs is sound (National Council on Public Works Improvement, 1988).

On the other hand, one-third of the non-Federal flood control dams inspected under the national non-Federal dam program were found to be unsafe, mostly due to inadequate spillways (National Council on Public Works Improvement, 1988). (Spillways are designed to prevent dam failure through overtopping.) These non-federal, smaller, mostly urban, flood control and stormwater structures may be more likely to have their capacity exceeded.

Some large dams may become susceptible to failure if storm intensity increases. The spillways of many large dams are designed to pass a "probable maximum flood" (an extreme flood event much greater than the 100-year flood). However, urbanization upstream from many dams is resulting in increased impervious surface (such as pavement) and increased peak runoff, and the probabilities of great floods, although remote, may increase due to climate change.

Hydropower

Because of the decline in water availability that could result from climate change, hydropower output and reliability could decline in the West and the Great Lakes. The Southeast could be facing the same problems unless it sacrificed or altered reservoir storage of streamflow increases in regions such as the Southeast hydropower production would increase also.

Recreation

Warmer and dryer conditions in the Southeast may increase the conflict between water uses, especially over reservoir releases and levels in the Tennessee Valley Authority region and the Lake Lanier, Georgia, systems. The conflicting uses may include releases for navigation, in-stream uses, urban water supply, groundwater recharge, hydropower and recreation (see Chapter 6).

NATIONAL POLICY IMPLICATIONS

Decreases in water availability, increased risk of flood damages, and the ensuing conflicts between water users competing for an increasingly scarce or difficult to manage resource are the major water resource issues raised by the possible impacts of a global warming trend. Some regions may restrict water use for lower value uses or may facilitate transfer of their water rights to higher value uses. How will we manage the transition to the new water resource regimes possible under climate change?

Current policy responses are complicated by the uncertainty attached to climate change forecasts. To be more helpful, the forecasts should be specific by area and should be accurate over the design-life of water resource structures. For example, they may depend in part on whether policymakers believe that the impacts will be felt as soon as 20 years from now or will occur gradually over 100 years. Forecasts of rapid climate changes may argue for measures to quickly prevent and avert climate change impacts; forecasts of gradual change may argue for policies that adapt and adjust to the change over time.

The implications of uncertainty include the following:

- Do not invest in irreversible, inflexible, large-scale, and high-cost measures.
- Design, modify, and rehabilitate structures and operating procedures that will provide robust and resilient water resource systems under different climate change scenarios.
- Implement a wide variety of measures for reducing demand, as long as they do not reduce the robustness and resilience of the systems.

Policy approaches to water resources may be grouped under supply (or structural) approaches and demand (or nonstructural) approaches. For example, water shortages may be addressed either by increasing developed supply (storage capacity) or decreasing water consumption and improving water quality.

Many or most of the policy approaches listed below have been recommended by water resource experts for 20 years. The potential impacts of climate change are an even greater impetus for implementing these policies.

Supply and Structural Policy Approaches

Developing Surface Water Structures

Surface water structures increase developed or available water supply or prevent flooding. These structures include dams, reservoirs, levees, and aqueducts.

Because of high costs of construction, adverse impacts on the environment and in-stream uses, limited sites available for new structures, and opposition by citizen groups, the trend during the past decade has been away from large excess-capacity, capital-intensive projects. Recent Federal financing for large structures has largely been limited to modifying, maintaining, and rehabilitating existing structures (Bureau of Reclamation, 1987). Only the Central Utah Project and the Central Arizona

Project have gone forward in recent years. Largely because of public opposition to new dams, only one major project in the Northeast has been completed in past 20 years -- the Bloomington Dam on the Potomac River. California citizens in 1982 voted down funds for the proposed Peripheral Canal that would increase diversion of water from north to south in the State. The trend toward local/state and away from federally financed projects has reduced funds available for large projects (National Council on Public Works Improvement, 1988).

These current trends in water resources management may be reevaluated in light of possible new demands for developed water supply under warm-dry climate change scenarios. Climate change may create pressure to build the Animas-La Plata and Narrows Projects proposed for Colorado, the Garrison Diversion in North Dakota, the Peripheral Canal in California, and structures to divert water from northern New England to southeastern Massachusetts.

Including Climate Change in Structural Design

Climate change should be a consideration in design and risk analysis for repair and replacement of existing projects and for constructing new projects (Hanchey et al., 1986). Current engineering and management approaches design for the mean, variability, and extremes of historical record. Large systems have substantial redundancy and robustness that enable them technologically and institutionally to adapt to large stresses (Matalas and Fiering, 1977). However, future climate may change hydrologic conditions from those on which the management of several major water systems is based.

In some cases, design includes both structural and nonstructural measures. Society may not be able to afford to build costly fail-safe water supply or flood control projects. For example, the design of Army Corps of Engineers' projects is increasingly becoming "safe-fail." This is a strategy of designing flood protection, for example, for less than the extreme event of record but for the 20- to 50-year flood, and then complementing the structural measure with emergency management plans that mitigate the damages (Hanchey et al., 1986).

Optimizing Water Resource Systems

Operational strategies for large-scale water systems and watersheds can have an enormous influence on the overall performance and resilience of the system and may provide additional water supplies to mitigate the impacts of climate change. Management practices may allow for substantial operating flexibility concerning releases of stored water. However, current design and management practices rely on historical data that may be superseded by new hydrologic averages and extremes.

Water yields may be substantially increased by operating existing facilities and surface and groundwater supplies as systems, rather than as independent projects (Sheer, 1985). For example, the Federal Bureau of Reclamation (1987) is adopting operational, management, or physical changes to gain more output from the same resources. Protection of groundwater recharge areas and methods for the conjunctive use of ground and surface waters are being implemented nationwide by water management agencies (Tripp and Jaffe, 1979; U.S. Water Resources Council, 1980).

Watershed management practices also affect water supply. For example, water yields can be significantly affected by timber harvest practices. Approximately 70-80% of water yield in the West is the result of snowmelt in high-elevation forests, much of which is under public jurisdiction (Troendle, 1983).

Demand Management and Nonstructural Policy Approaches

The limitations of supply and structural solutions to the nation's water problems may argue that greater attention should be given to demand management to resolve long-term water resource problems and to mitigate the potential adverse impacts of climate change. In the past, water was considered too essential a resource or too insensitive to price for its use to be allocated by market forces during shortages. Policy took the form of direct controls and appeals to conserve (Hrezo et al., 1986). In recent years, greater attention has been given to institutional, legal, and market policies to allocate and regulate limited water supplies among competing uses and to promote water conservation.

Reducing Irrigation Use

Relatively small reductions in the percentage of irrigation demand can make large amounts of water available for higher value urban and industrial uses. For instance, nearly 83% of withdrawals and 90% of the consumptive use of western water is for irrigation. Consequently, a 10% reduction in irrigation use may save 20 million acre-feet (maf) in water withdrawn and 10 maf in water consumed annually. This would save an amount approximately equal to the average annual flow of the Upper Colorado River Basin and would double the water available for municipal and industrial uses in the West (Frederick, 1986).

Estimates of water savings through improved efficiencies in irrigation management range between 20 and 50 % (Viessman and DeMoncada, 1980). Due in part to decreased availability, increased costs of pumping groundwater, and opportunities to market water rights to higher value users, irrigation declined 6 % from 1980 to 1985 (Solley et al., 1988).

Inexpensive water was a key factor in the settlement of the West and the expansion of agriculture (Frederick, 1986). The Bureau of Reclamation was established early in this century to promote the development of irrigation in the West. The Bureau provides irrigation for about 11 million acres, more than one-fifth of the total irrigated acreage. In 1975, it supplied 28.1 maf of water, 93% of which was used for irrigation (Bureau of Reclamation, 1976). Since the Bureau accounts for nearly one-third of all surface water deliveries and about one-fifth of total water deliveries in the 17 Western States, using this water more efficiently could be very important.

In the past, demand for Bureau water was not based on the real cost of the water, because more than 90% of the Bureau's irrigation projects have been subsidized, and payments on some projects no longer even pay for operation and maintenance (Frederick and Hansen, 1982). Irrigators fortunate enough to receive such inexpensive water may have little or no incentive to conserve. However, the Bureau's more recently stated objectives include revising their water marketing policy, promoting conservation, and pricing water to reflect its real cost (Bureau of Reclamation, 1987).

The 1985 Food Security Act and programs managed by the U.S. Department of Agriculture encourage water conservation and maintenance of water quality (Rosenberg, 1988). USDA programs focus on conserving soil and water, setting aside crops, and retiring marginal lands.

Municipal and Industrial Water Use

Municipalities throughout the country are finding it difficult and expensive to augment their supplies to meet the demands of population and economic growth. Traditional average-cost pricing designed to provide adequate service to customers and returns to water companies is being reevaluated (Congressional Budget Office, 1987). Average-cost pricing and declining-block rates tend to cause overinvestment in system capacity and overuse of existing capacity. Marginal-cost pricing or progressive-rate structures (charging for the actual amount of water used) can reduce domestic and industrial water consumption because water use is sensitive to price (Gibbons, 1986).

Water Markets and Transfers in the West

It is unlikely that the Federal Government will subsidize many more large irrigation projects. Instead, conservation incentives, prices, and water markets are becoming important management tools to balance water demand with supplies. Evidence shows that many water uses, including irrigation, are sensitive to price (Gibbons, 1986). However, while irrigators in may cases can adjust to higher prices and to water market opportunities, incentives for abandoning traditional water-intensive practices are still lacking for many areas in the West.

The "first in time, first in right" appropriation doctrine, which favors the longest standing water rights, governs much of the West's surface water and some groundwater. It encourages economic development by guaranteeing users a secure supply of water. This doctrine was potentially an important step for creating clear, transferable property rights to water -- a precondition for effective operation of water markets. The potential for water transfers to the highest value users has not yet been fully realized because the nature and transferability of the rights are obscured by legal and administrative factors (Trelease, 1977; Frederick, 1986; Saliba et al., 1987). Following are some examples.

- Rather than grant absolute ownership, States with prior appropriation rules grant rights to use water for beneficial purposes. Water rights not put to beneficial use may be forfeited. This encourages a use-it-or-lose-it attitude.

- Federal and Native American water rights remain unquantified in some areas, such as the Colorado River Basin.

- The U.S. Department of the Interior's Bureau of Reclamation supplies 30% of the irrigation water in the West. There are few incentives to conserve this water, because the Bureau's long-term, interest-free repayment contracts keep the price low and limit opportunities to transfer the water to users willing to pay more.

- Because of imperfect competition, third-party effects, uncertainty over administrative rules, and equity considerations, water market prices may not appropriately measure water values according to economic efficiency criteria (Gibbons, 1986; Saliba et al., 1987).

- It is possible to control groundwater withdrawals, but for a number of reasons it is difficult to establish market mechanisms for groundwater allocation. Because all groundwater users essentially draw from a shared pool, groundwater resources are treated as "common property." As a result, property rights are difficult to define, third- party impacts of transfers of groundwater rights are significant, and interstate agreements concerning allocation of interstate aquifer water are difficult to attain (Emel, 1987).

Despite the obstacles, transfer of water rights among users -- especially from irrigators to municipalities and power companies seeking water for urban expansion and electricity production -- is becoming common in many Western States (Wahl and Osterhoudt, 1985; Frederick, 1986). Methods include negotiated purchases, short-term exchanges during droughts, and water banks and markets (Wahl and Osterhoudt, 1985; Saliba et al., 1987; Wahl and Davis, 1986).

Legislation in many Western States has facilitated water transfers (Frederick, 1986; Frederick and Kneese, 1988). Arizona's new water law facilitates the purchase of land with water rights and the use of that water for urban development. Strict technical standards imposing conservation on municipal and industrial water uses, such as watering golf courses with wastewater, are also part of Arizona's laws (Saliba et al., 1987). California has applied the public trust doctrine to modify existing permits to require flow releases to protect the Sacramento-San Joaquin Delta from saltwater intrusion (Tarlock, 1987). Montana is increasingly basing water management plans on its in-stream flow requirements and is exploring ways to have these requirements for all future beneficial in-stream uses count as a bona fide use of the Missouri River in order to slow the rate of growth of diversion of water for off-stream uses (Tarlock, 1987). The Supreme Court decided in Colorado v. New Mexico (456 U.S. 176 (1982)) that equitable apportionment may be used to override prior appropriation priorities in cases of major flow reductions. The Supreme Court specifically mentioned climatic conditions in ruling that prior appropriation systems would otherwise protect arguably wasteful and inefficient uses of water at the expense of other uses.

Frederick and Kneese (1988) caution that water transfers occur gradually and are not likely to affect more than a small percentage of agricultural water rights for the foreseeable future. However, legal and institutional changes facilitating water markets and demand for water by high-value users may be accelerated under the stress of climate change (Trelease, 1977).

Interstate and Regional Compacts and Commissions

River basin and aquifer boundaries in many cases traverse or underlie portions of several States. Regional and interstate cooperation to manage water resources has a long tradition in some U.S. river basins. Implementing the agreements required for regional compacts and operating procedures and sharing of water supplies may require substantial and lengthy negotiations. However, the cost savings also can be substantial (Sheer, 1985).

Several interstate water authorities have significant allocation authority. For example, the Delaware River Basin Commission allocates water to users in the Delaware Basin and transfers it to New York City. It does so by the authority of a 1954 Supreme Court ruling (347 U.S. 995) and Federal legislation establishing the Commission in 1961 and granting it regulatory, licensing, and project construction powers. Similarly, water authorities in the Washington, D.C., metropolitan area operate Potomac River water supply projects as integrated systems under a 1982 agreement. Both the Delaware and Potomac regional compacts include provisions for drought allocations. (See Harkness et al., 1985, for management actions taken by the Delaware River Basin Commission during a 1984-85 drought.) Sheer (1985) estimated that coordinated water authority activities in the Potomac River Basin eliminated the need for new reservoirs, saving from $200 million to $1 billion. In the West, the most prominent interstate agreement is the Colorado River Compact, which divides river water allocations among seven Western States and Mexico (see Weatherford and Brown, 1986).

Numerous opportunities exist around the country for interstate, intrabasin, and interbasin coordination of water deliveries. In the East, consolidation of or coordination among fragmented urban water supply authorities can achieve economies of scale in water delivery, decrease the risk of shortage in any one subsystem within a region, and provide drought management procedures (Sheer, 1985).

Drought Management Policies

Integrating drought planning into water resource management may assume greater priority if climate change causes water shortages. The Model Water Use Act (Hrezo et al., 1986) advocates that states or water supply authorities integrate drought management and advance planning into their policies by designating a governmental authority for drought response and adopting mechanisms for automatically implementing and enforcing water use restrictions. In 1986, only seven States had comprehensive management plans for water shortages (Hrezo et al., 1986). Most States rely on general water rights, emergency responses, and litigation to allocate water during shortages.

Water Quality

Federal and State legislation and regulations for control of in-stream water quality have had a dramatic effect on reducing conventional water pollutants since the enactment of the 1972 Clean Water Act. However, some persistent water quality problems remain to be addressed (see USEPA, 1987b). In some cases, where river and lake levels are lower, more stringent controls on point and nonpoint sources may be required to meet water quality standards.

Many States have adopted measures to protect in-stream water uses. These include reserving flows or granting rights for particular in-stream uses and directing agencies to review impacts before granting new rights (U.S. Water Resources Council, 1980; Frederick and Kneese, 1988). Regulations limiting water use may have to be modified under some climate change scenarios that forecast increased incidence of low flows in some regions.

Policies for Floodplains

The National Flood Insurance Program was enacted in 1968, with major amendments in 1973. The program provides subsidized flood insurance for existing structures in flood-prone areas, provided that the community with jurisdiction regulates the location and construction of new buildings to minimize future flood losses. New structures that comply with the restrictions are eligible for insurance at full actuarial rates.

The program is second only to the Social Security Act in the magnitude of potential government liability. In 1979, the program took in $140 million in premiums and paid $480 million in payment claims. Recently, the program was authorized to apply claims payments to relocation expenses for structures exposed to repeated flood or erosion damage.

Where rainfall and flooding increase, the 100-year floodplain would expand, and rate maps would need revision. Premium payments and claims would rise.

RESEARCH NEEDS

1. Refine global climate change models so that water resource engineers and managers in regional planning can use their predictions more confidently.

2. Monitor atmospheric, oceanic, and hydrological conditions to detect evidence of water resource impacts of climate change.

3. Conduct research to identify implementable opportunities for adjusting and adapting to climate change. Types of research include the following:

    - Identify and quantify the relative vulnerabilities of water uses to climate change.

    - Focus research and monitoring on vulnerable water resource areas, such as the western edge of the Great Plains, where moisture is the limiting factor for agriculture, and river basins where demand is greater than developed safe yield supply under current conditions.

    - Quantify Federal and Native American water rights in the West.

    - Along with estimating how much water may be required for the various uses, develop information on the cost and worth or value of water in the various uses.

    - Examine how present institutions can better allocate water among users and provide incentives to conserve water and assess the extent to which laws and regulations exacerbate the effects of climate change (examples include thermal controls for rivers and Federal pricing and reallocation policies for irrigation water).

- Identify, project, and quantify economic, demographic, and institutional adjustments that may accompany climate induced impacts on water resources in the absence of concerted public action to provide data upon which to base policy decisions regarding action alternatives.

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CHAPTER 9

SEA LEVEL RISE

FINDINGS

Global warming could cause a sea level rise of 0.5 to 2m by 2100. Such a rise would inundate wetlands and lowlands, erode beaches, exacerbate coastal flooding, and increase the salinity of estuaries and aquifers.

- A one-meter rise by the year 2100 could drown approximately 25 to 80 percent of the U.S. coastal wetlands. Their ability to survive would depend largely on whether they could migrate inland or whether levees and bulkheads block their path of migration.
- A one-meter rise could inundate 5,000-10,000 square miles of dryland if shores are not protected, and 4,000-9,000 square miles of dryland if only developed areas are protected.
- Most coastal barrier island communities would probably respond to sea level rise by raising land with sand pumped from offshore. Wide and heavily urbanized islands may use levees, while communities on lightly developed islands may adjust to a gradual landward migration of the islands.
- Protecting developed areas against such inundation and erosion by building of bulkheads and levees, pumping sand, and raising barrier islands would cost $73-111 billion (cumulative capital costs in 1985 dollars) for a one-meter rise by the year 2100.
- Developed barrier islands would likely be protected from sea level rise because of their high property values. However it would cost $50-75 billion (cumulative capital costs in 1985 dollars) to elevate beaches, houses, land, and roadways by the year 2100.

Policy Implications

- Many of the necessary responses to sea level rise need not be implemented until the rise is imminent, such as rebuilding ports, constructing levees, and pumping sand onto beaches. On the other hand, the cost of incorporating sea level rise into a wide variety of engineering and land use decisions would be negligible compared to the costs of not responding until sea level rises.
- Wetland ecosystems are likely to survive sea level rise only if appropriate measures are implemented soon. At the states and local levels, these measures include land use planning,

regulation, and redefinitions of property rights. The State of Maine has already issued regulations to enable wetlands to migrate landward by requiring that structures be removed as sea level rises.

- The coastal wetlands protected under Section 404 of the Clean Water Act will gradually be inundated. The Act does not authorize measures to ensure survival of wetland ecosystems as sea level rises. Additional statutory authorities might be needed to protect migrating wetlands.
- The National Flood Insurance Program may wish to consider the implications of examining the sea level rise on potential liabilities. A recent HUD authorization act requires this program to purchase property threatened with erosion. The act may imply a commitment by the federal government to compensate property owners for losses due to sea level rise.

CAUSES, EFFECTS, AND RESPONSES

Introduction

The global warming from the greenhouse effect could raise sea level approximately one meter by expanding ocean water, melting mountain glaciers, and causing ice sheets in Greenland to melt or slide into the oceans. Such a rise would inundate coastal wetlands and lowlands, erode beaches, increase the risk of flooding, and increase the salinity of estuaries, aquifers, and wetlands.

In the last five years, many coastal communities throughout the world have started to prepare for the possibility of such a rise. In the United States, Maine has enacted a policy declaring that shorefront building will have to be moved to enable beaches and wetlands to migrate inland to higher ground. Maryland has shifted its shore-protection strategy from a technology that can not accommodate sea level rise to one that can. Seven coastal states have held large public meetings on how to prepare for a rising sea. Australia and the Netherlands are beginning to undergo a similar process.

Causes

Ocean levels have always fluctuated with changes in global temperatures. During the ice ages when the earth was 5°C (9°F) colder than today, much of the ocean's water was frozen in glaciers and sea level often was more than 100 meters (300 feet), below the present level (Donn et al., 1962; Kennett, 1982; Oldale, 1985). Conversely, during the last interglacial period

(100,000 years ago) when the average temperature was about 1°C (2°F) warmer than today, sea level was approximately 20 feet higher than current sea level (Mercer, 1968).*

When considering shorter periods of time, worldwide sea level rise must be distinguished from relative sea level rise. Although climate change alters worldwide sea level, the rate of sea level rise relative to a particular coast has greater practical importance and is all that monitoring stations can measure. Because most coasts are sinking (and a few are rising), the range of relative sea level rise varies from more than 3 feet per century in Louisiana and parts of California and Texas to 1 foot per century along most of the Atlantic and Gulf coasts, and to a slight drop in much of the Pacific Northwest (Figure 9-1). Areas such as Louisiana provide natural laboratories for assessing the possible effects of future sea level rise (Lyle et al., 1987).

Global sea level trends have generally been estimated by combining the trends at tidal stations around the world. Studies combining these measurements suggest that during the last century, worldwide sea level has risen 10 to 15 cm (4 to 6 inches) (Barnett, 1984; Fairbridge and Krebs, 1962). Much of this rise has been attributed to the global warming that has occurred during the last century (Meier, 1984; Gornitz et al., 1982). Hughes (1983) and Bentley (1983) estimated that a complete disintegration of West Antarctica in response to global warming would require a 200- to 500-year period, and that such a disintegration would raise sea level 20 feet. Most recent assessments, however, have focused on the likely rise by the year 2100. Figure 9-2 illustrates recent estimates of sea level rise, which generally fall into the range of 50 to 200 cm.

Although most studies have focused on the impact of global warming on global sea level, the greenhouse effect would not necessarily raise sea level by the same amount everywhere. Removal of water from the world's ice sheets would move the earth's center of gravity away from Greenland and Antarctica and would thus redistribute the oceans' water toward the new center of gravity. Along the U.S. coast, this effect would generally increase sea level rise by less than 10%. Sea level could actually drop, however, at Cape Horn and along the coast of Iceland. Climate change could also effect local influences on sea level by changing ocean currents, winds, and atmospheric pressure; no one has estimated these impacts.

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*Other processes such as changes in ocean basins have also played a role, albeit over longer periods of time.

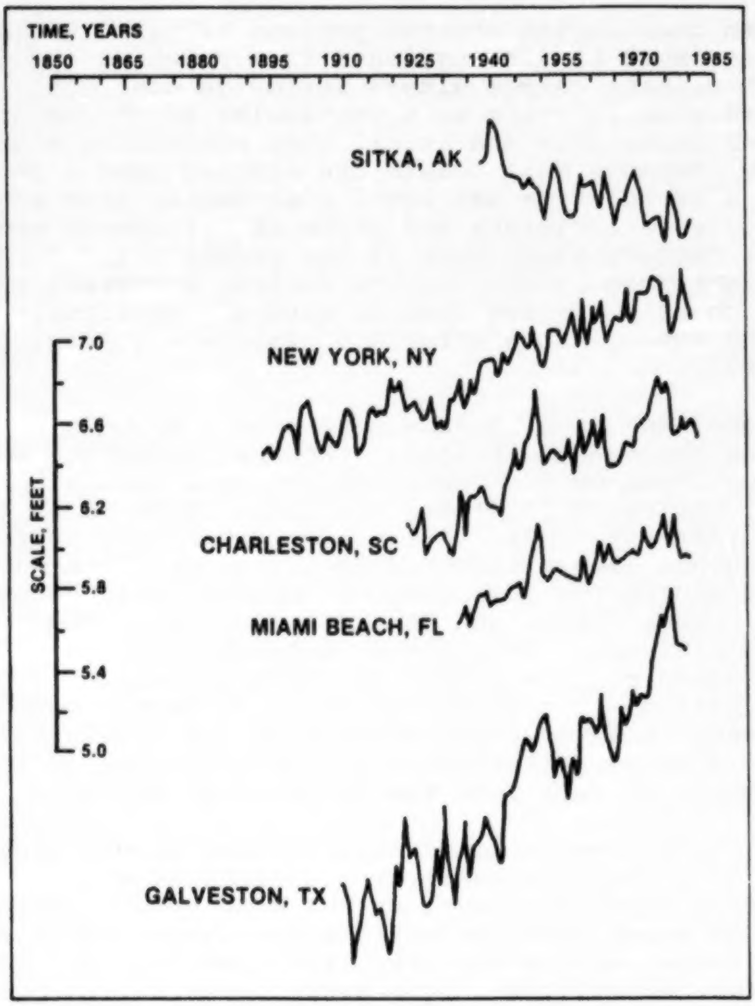


Figure 9-1. Time Series Graph of Sea Level Trends for New York, Charleston, Miami, Galveston, and Sitka

Source: Lyle et al, 1987.

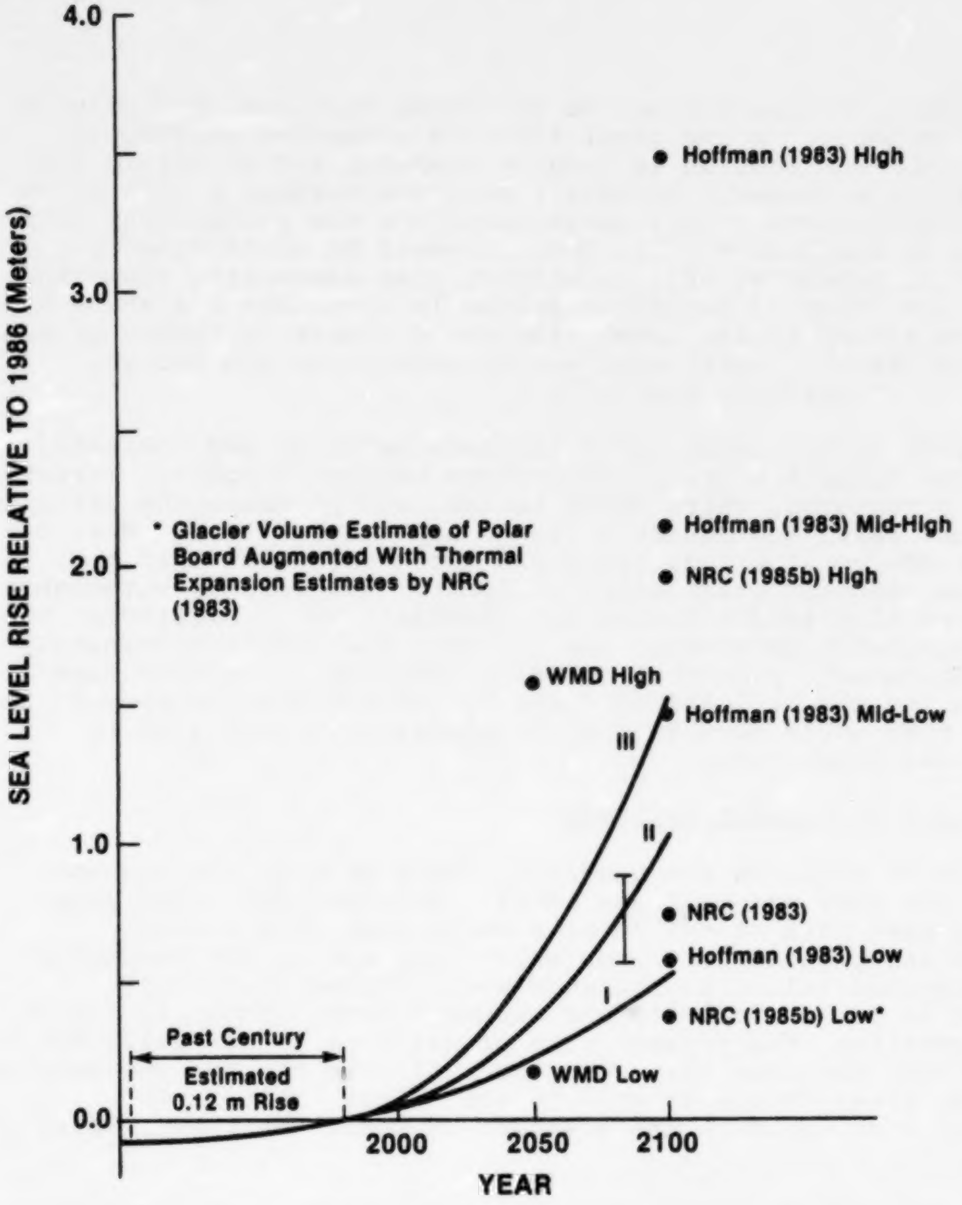


Figure 9-2. Estimates of Future Sea Level Rise

Source: Hoffman (1983, 1986); Meier (1985); Revelle (1983); Wigley (1987, Thomas

Effects

In this section and in the following sections, the effects of, and responses to sea level rise are presented separately. However, the distinction is largely academic and is solely for presentation purposes. In many cases, the responses to sea level rise are sufficiently well-established and the probability of no response is sufficiently low that it would be misleading to discuss the potential effects without also discussing responses. For example, much of Manhattan Island is less than 2 m above high tide; the effect of sea level rise would almost certainly be the increased use of coastal engineering structures and not the inundation of downtown New York.

A rise in sea level would inundate wetlands and lowlands, accelerate coastal erosion, exacerbate coastal flooding, threaten coastal structures, raise water tables, and increase the salinity of rivers, bays, and aquifers (Barth and Titus, 1984). Most of the wetlands and lowlands are found along the Gulf coast and along the Atlantic coast south of central New Jersey, although a large area also exists around San Francisco Bay. Similarly, the areas vulnerable to erosion and flooding are also predominately in the Southeast; potential salinity problems are spread more evenly along the U.S. Atlantic coast. We now discuss some of the impacts that would result if no responses were initiated to address sea level rise.

Destruction of Coastal Wetlands

Coastal wetlands are generally found between the highest tide of the year and mean sea level. Wetlands have kept pace with the past rate of sea level rise because they collect sediment and produce peat upon which they can build; meanwhile they, expanded inland as lowlands were undated (Fig 9-3). Wetlands accrete vertically and expand inland. Thus, as Figure 9-2 illustrates, the present area of wetlands is generally far greater than the area that would be available for new wetlands as sea level rises (Titus et al., 1984b; Titus, 1986). The potential loss would be the greatest in Louisiana (see Chapter 6, Southeast.)

In many areas, people have built bulkheads just above the marsh. If sea level rises, the wetlands would be squeezed between the sea and the bulkheads (see Figure 9-3). Previous studies have estimated that if the development in coastal areas is removed to allow new wetlands to form inland, a 1.5- to 2-m rise would destroy 30 to 70% of the U.S. coastal wetlands. If levees and bulkheads are erected to protect today's dry land, the loss could be 50 to 80% (Park, 1986; Titus, 1988; Armentano et al., 1988). Such a loss would reduce the available habitat for

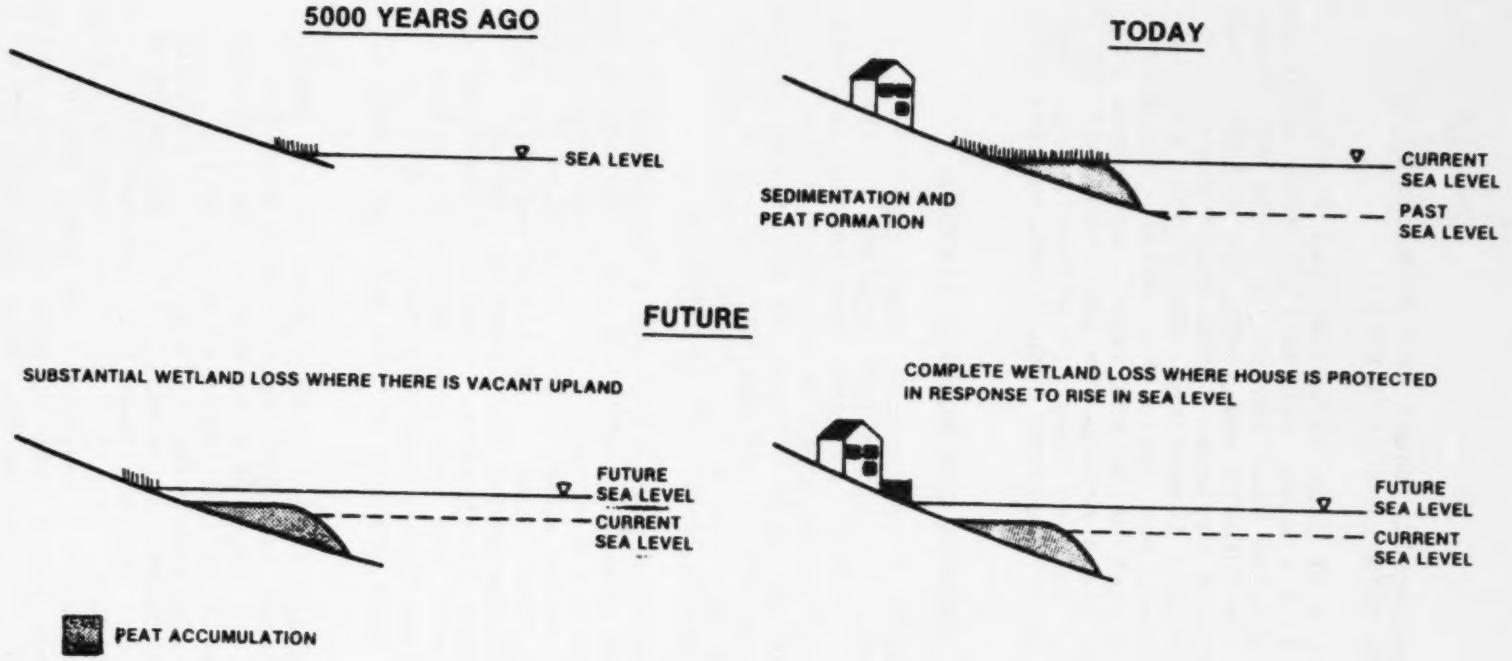

5000 YEARS AGO
SEA LEVEL
TODAY
SEDIMENTATION AND PEAT FORMATION
CURRENT SEA LEVEL
PAST SEA LEVEL
FUTURE
SUBSTANTIAL WETLAND LOSS WHERE THERE IS VACANT UPLAND
FUTURE SEA LEVEL
CURRENT SEA LEVEL
COMPLETE WETLAND LOSS WHERE HOUSE IS PROTECTED IN RESPONSE TO RISE IN SEA LEVEL
FUTURE SEA LEVEL
CURRENT SEA LEVEL
PEAT ACCUMULATION

Figure 9-3. Evolution of marsh as sea rises. Coastal marshes have kept pace with the slow rate of sea level rise that has characterized the last several thousand years. Thus, the area of marsh has expanded over time as new lands were inundated. If in the future, sea level rises faster than the ability of the marsh to keep pace, the marsh area will contract. Construction of bulkheads to protect economic development may prevent new marsh from forming and result in a total loss of marsh in some areas.

Source: Titus, 1986.

birds and juvenile fish and would reduce the production of organic materials on which estuarine fish rely.

The dry land within 2 m of high tide includes forests, farms, low parts of some port cities, cities that sank after they were built and are now protected with levees, and the bay sides of barrier islands. The low forests and farms are generally in the mid-Atlantic and Southeast regions; these would provide potential areas for new wetland formation. Major port cities with low areas include Boston, New York, Charleston, and Miami. New Orleans is generally 8 feet below sea level, and parts of Galveston, Texas City, and areas around the San Francisco Bay are also well below sea level. Because they are already protected by levees, these cities are more concerned with flooding than with inundation.

Inundation and Erosion of Beaches and Barrier Islands

Some of the most important vulnerable areas are the recreational barrier islands and spits (peninsulas) of the Atlantic and Gulf coasts. Coastal barriers are generally long narrow islands and spits with the ocean on one side and a bay on the other. Typically, the oceanfront block of an island ranges from 5 to 10 feet above high tide, and the bay side is 2 to 3 feet above high water. Thus, even a 1-m sea level rise would threaten much of this valuable land with inundation.

Erosion threatens the high part of these islands and is generally viewed as a more immediate problem than the inundation of the bay sides. As Figure 9-4 shows, a rise in sea level can cause an ocean beach to retreat considerably more than it would from the effects of inundation alone. The visible part of the beach is much steeper than the underwater portion, which comprises most of the active "surf zone." While inundation alone is determined by the slope of the land just above the water, Bruun (1962) and others have shown that the total shoreline retreat from a sea level rise depends on the average slope of the entire beach profile.

Previous studies suggest that a 1-foot rise in sea level would generally cause beaches to erode 50-100 feet from the Northeast to Maryland (e.g., Kyper and Sorensen, 1985; Everts, 1985); 200 feet along the Carolinas (Kana et al., 1984); 100-1,000 feet along the Florida coast (Bruun, 1962); 200-400 feet along the California coast (Wilcoxen, 1986); and perhaps several miles in Louisiana. Because most U.S. recreational beaches are less than 100 feet wide at high tide, even a 1-foot rise in sea level would require a response. In many areas, undeveloped barrier islands could keep up with rising sea level by "overwashing" landward. In Louisiana, however, barrier

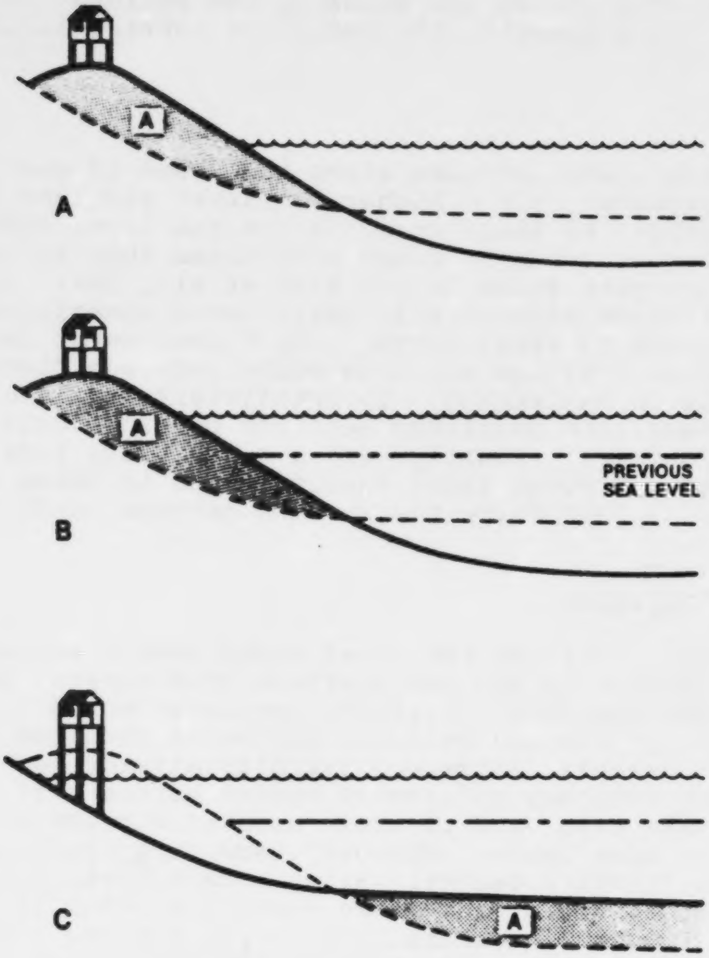


Figure 9-4. The Bruun Rule. A, initial condition; B, Immediate inundation when sea level rises; C, subsequent erosion due to sea level rise. A rise in sea level immediately results in shoreline retreat due to inundation, shown in the first two examples. However, a 1 m rise in sea level implies that the offshore bottom must also rise 1 m. The sand required to raise the bottom (A') can be supplied by beach nourishment. Otherwise, waves will erode the necessary sand (A) from upper part of the beach as shown in C.

Source: Titus, 1986.

islands are breaking up and exposing the wetlands behind them to gulf waves; consequently, the Louisiana barrier islands have rapidly eroded.

Flooding

Flooding would increase along the coast if sea level rises for three reasons: (1) A higher sea level provides a higher base for storm surges to build upon. A 1-m sea level rise would enable a 15-year storm to flood many areas that today are flooded only by a 100-year storm (e.g., Kana et al., 1984; Leatherman, 1984). (2) Beach erosion also would leave oceanfront properties more vulnerable to storm waves. (3) Higher water levels would reduce coastal drainage and thus would increase flooding attributable to rainstorms. In artificially drained areas such as New Orleans, the increased need for pumping could exceed current capacities. Finally, (4) a rise in sea level would raise water tables and would flood basements and in cases where the groundwater is just below the surface perhaps leach it above the surface.

Saltwater Intrusion

Finally, a rise in sea level would enable saltwater to penetrate farther inland and upstream into rivers, bays, wetlands, and aquifers. Salinity increases would be harmful to some aquatic plants and animals, and would threaten human uses of water. For example, increased salinity already has been cited as a factor contributing to reduced oyster harvests in the Delaware and Chesapeake Bays, and to conversion of cypress swamps in Louisiana to open lakes. Moreover, New York, Philadelphia, and much of California's Central Valley obtain their water from areas located just upstream from areas where the water is salty during droughts. Farmers in central New Jersey and the city of Camden rely on the Potomac-Raritan-Magothy aquifer, which could become salty if sea level rises (Hull and Titus, 1986). The South Florida Water Management District already spends millions of dollars every year to prevent Miami's Biscayne Aquifer from becoming contaminated with seawater.

Responses

The possible responses to inundation, erosion, and flooding fall broadly into three categories: erecting walls to hold back the sea, allowing the sea to advance and adapting to the advance, and raising the land. Both the slow rise in sea level over the last thousand years and the areas where land has been sinking more rapidly offer numerous historical examples of all three responses.

For over five centuries, the Dutch and others have used dikes and windmills to prevent inundation from the North Sea. By contrast, many cities have been rebuilt landward as structures have eroded; the town of Dunwich, England, has rebuilt its church seven times in the last seven centuries. More recently, rapidly subsiding communities (e.g., Galveston, Texas) have used fill to raise land elevations; the U.S. Army Corps of Engineers and coastal States regularly pump sand from offshore locations to counteract beach erosion. Venice, a hybrid of all three responses, has allowed the sea to advance into the canals, has raised some lowlands, and has erected storm protection barriers.

Most assessments in the United States have concluded that low-lying coastal cities would be protected with bulkheads, levees, and pumping systems, and that sparsely developed areas adapt to a naturally retreating shoreline (e.g., Dean etal., 1987; Gibbs, 1984; Schelling, 1983). This conclusion has generally been based on estimates that the cost of structural protection would be far less than the value of the urban areas being protected but would be greater than the value of undeveloped land.

Studies on the possible responses of barrier islands and moderately developed mainland communities show less agreement but generally suggest that environmental factors would be as important as economics. Some have suggested that barrier islands should use seawalls and other "hard" engineering approaches (e.g., Kyper and Sorensen, 1985; Sorensen, 1984). Others have pointed to the aesthetic problems associated with losing beaches and have advocated a gradual retreat from the shore (Howard et al., 1985). Noting that new houses on barrier islands are generally elevated on pilings, Titus (1986) suggested that communities could hold back the sea but keep a natural beach by extending the current practice of pumping sand onto beaches to raising entire islands in place.

Responses to erosion are more likely to have adverse environmental impacts along sheltered water than on the open coast (Titus, 1986). Because the beach generally is a barrier island's most important asset, economics would tend to encourage these communities to preserve their natural shorelines; actions that would prevent the island from breaking up also would protect the adjacent wetlands. However, along most mainland shorelines, economic self-interest would encourage property owners to erect bulkheads; these would prevent new wetland formation from offsetting the loss of wetlands that were inundated.

Most of the measures for counteracting saltwater intrusion attributable to sea level rise have also been employed to address current problems. For example, the Delaware River Basin

Commission protects Philadelphia's freshwater intake on the river and New Jersey aquifers recharged by the river by storing water in reservoirs during the wet season and releasing it during droughts, thereby forcing the saltwater back toward the sea. Other communities have protected coastal aquifers by erecting underground barriers and by maintaining freshwater pressure through the use of impoundments and injection wells.

HOLDING BACK THE SEA: A NATIONAL ASSESSMENT

The studies referenced in the previous section have illustrated a wide variety of possible effects from and responses to a rise in sea level from the greenhouse effect. Although they have identified the implications of the risk of sea level rise for specific locations and decisions, these studies have not estimated the nationwide magnitude of the impacts. This report seeks to fill that void.

It was not possible to estimate the nationwide value of every impact of sea level rise. The studies thus far conducted suggest that the majority of the environmental and economic costs would be associated with shoreline retreat and measures to hold back the sea, which can be more easily assessed on a nationwide basis, thus other impacts. Because the eventual impact will depend on what people actually do, a number of important questions can be addressed within this context:

- Would a gradual abandonment of moderately developed mainland areas significantly increase the amount of wetlands that survived a rise in sea level?
- Would the concave profiles of coastal areas ensure that more wetlands would be lost than gained, regardless of land-use decisions?
- Should barrier islands be raised in place by pumping sand and elevating structures and utilities?
- Would a landward migration of developed barrier islands or to encircling them with dikes and levees be feasible alternatives?
- How much property would be lost if barrier islands were abandoned?

STRUCTURE OF STUDIES FOR THIS REPORT

Figure 9-5 illustrates the relationships between the various studies. As the top portion shows, investigators began with a case study of Long Beach Island, New Jersey. A case study was due to develop and evaluate methods for the national analysis. The Park and Leatherman studies performed the same calcualtion for the case study and the other sites included in the national assessment, with Park estimating the loss of wetlands and dryland, and Leatherman estimating the cost of dredging sufficient sand to raise recreational beaches and coastal barrier islands. However, Weggel and Yohe conducted detailed assessments for the case study that were not repeated for the other sites; the results were used in the Leatherman and Titus studies.

A central theme underlying these questions is that the implications of sea level rise for a community depend greatly on whether people adjust to the natural impact of shoreline retreat or undertake efforts to hold back the sea. Because no one knows the extent to which each of these approaches would be applied, this study was designed to estimate the impacts of sea level rise for (1) holding back the sea, and (2) natural shoreline retreat.

The tasks were split into five discreet projects:

1. Park et al. estimated the loss of coastal wetlands and dryland.
2. Leatherman estimated the cost of pumping sand onto open coastal beaches and barrier islands.
3. Weggel et al. estimated the cost of protecting sheltered shores with leaves and bulkheads.
4. Yohe began a national economic assessment by estimating the value of threatened property.
5. Titus and Greene synthesized the results of other studies to estimate ranges of the nationwide impacts.

Figure 9-5 illustrates the relationships between the various reports. As the top portion shows, the assessment began with a case study of Long Beach Island, New Jersey, which was necessary for evaluating methods and providing data for purposes of extrapolation. The Park and Leatherman studies performed the same calculations for the case study site that they would subsequently perform for the other sites in the nationwide analysis. However, Weggel and Yohe conducted more detailed assessments of the case study whose results were used in the Leatherman and Titus studies.

Because it would not be feasible for Leatherman to examine more than one option for the cost of protecting the open coast, Weggel estimated the cost of protecting Long Beach Island by

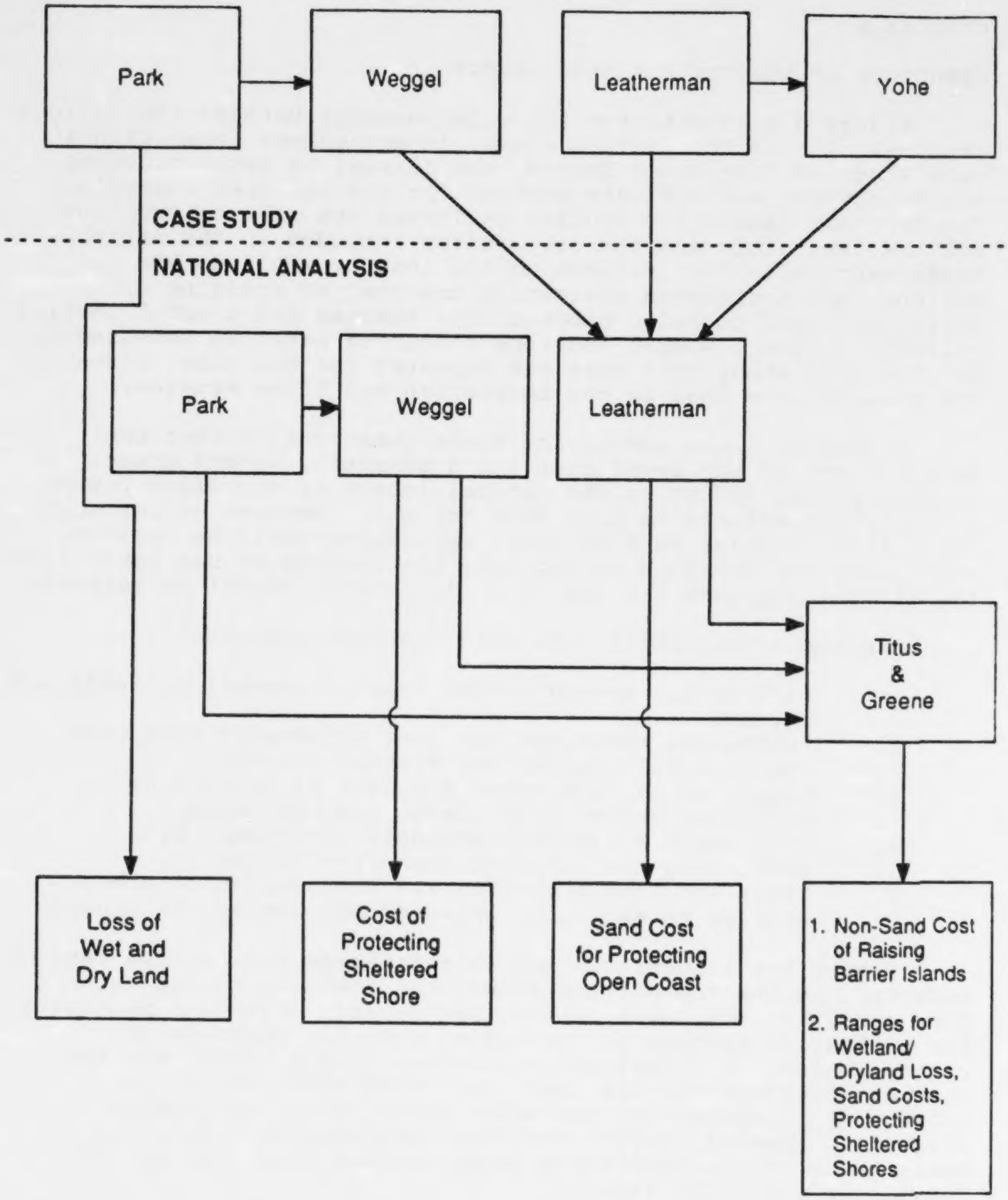

Park
Weggel
Leatherman
Yohe
CASE STUDY
NATIONAL ANALYSIS
Park
Weggel
Leatherman
Titus & Greene
Loss of Wet and Dry Land
Cost of Protecting Sheltered Shore
Sand Cost for Protecting Open Coast
1. Non-Sand Cost of Raising Barrier Islands
2. Ranges for Wetland/ Dryland Loss, Sand Costs, Protecting Sheltered Shores

Figure 9-5. Overview of Sea Level Rise Studies-Authors

three approaches: (1) raising the island in place; (2) gradually rebuilding the island landward; and (3) encircling the island with dikes and levees; Yohe estimated the value of threatened structures. Titus analyzed Weggel's and Yohe's results and concluded that raising barrier islands would be the most reasonable option for the Leatherman study. They also noted that the cost of this option would be considerably less than the resources that would be lost if the islands are not protected as shown in Figure 9-6.

Once the case study was complete, Park, Leatherman, and Weggel proceeded independently with their studies (although Park provided Weggel with elevation data). When those studies were complete, Titus synthesized their results, developing a nationwide estimate of the cost of holding back the sea and interpolating Weggel's 200-cm results for the 50- and 100-cm scenarios.

In presenting results from the Park and Weggel studies, the sites were grouped into seven coastal regions, four of which are in the Southeast: New England, mid-Atlantic, south Atlantic, south Florida/gulf coast peninsula, Louisiana, other gulf (Texas, Mississippi, Alabama, Florida Panhandle), and the Pacific coast. Figure 9-7 illustrates these regions.

SCENARIOS OF SEA LEVEL RISE

Although the researchers considered a variety of scenarios of future sea level rise, this report focuses on the impacts of three scenarios: rises of 50, 100, and 200 cm by the year 2100. Following this convention of a recent National Research Council report (Dean et al., 1987), the rise was interpolated throughout the 21st century using a parabola, as shown in Figure 9-8. For each site, local subsidence was added to determine relative sea level rise. Along the coast of Florida (which is typical of most of the U.S. coast), sea level would rise 1 foot by 2025, 2040, and 2060 for the three scenarios and 2 feet by 2045, 2065, and 2100.

RESULTS OF SEA LEVEL STUDIES IN THIS REPORT

Loss of Coastal Wetlands and Dryland

Park sought to test a number of hypotheses presented in previous publications:

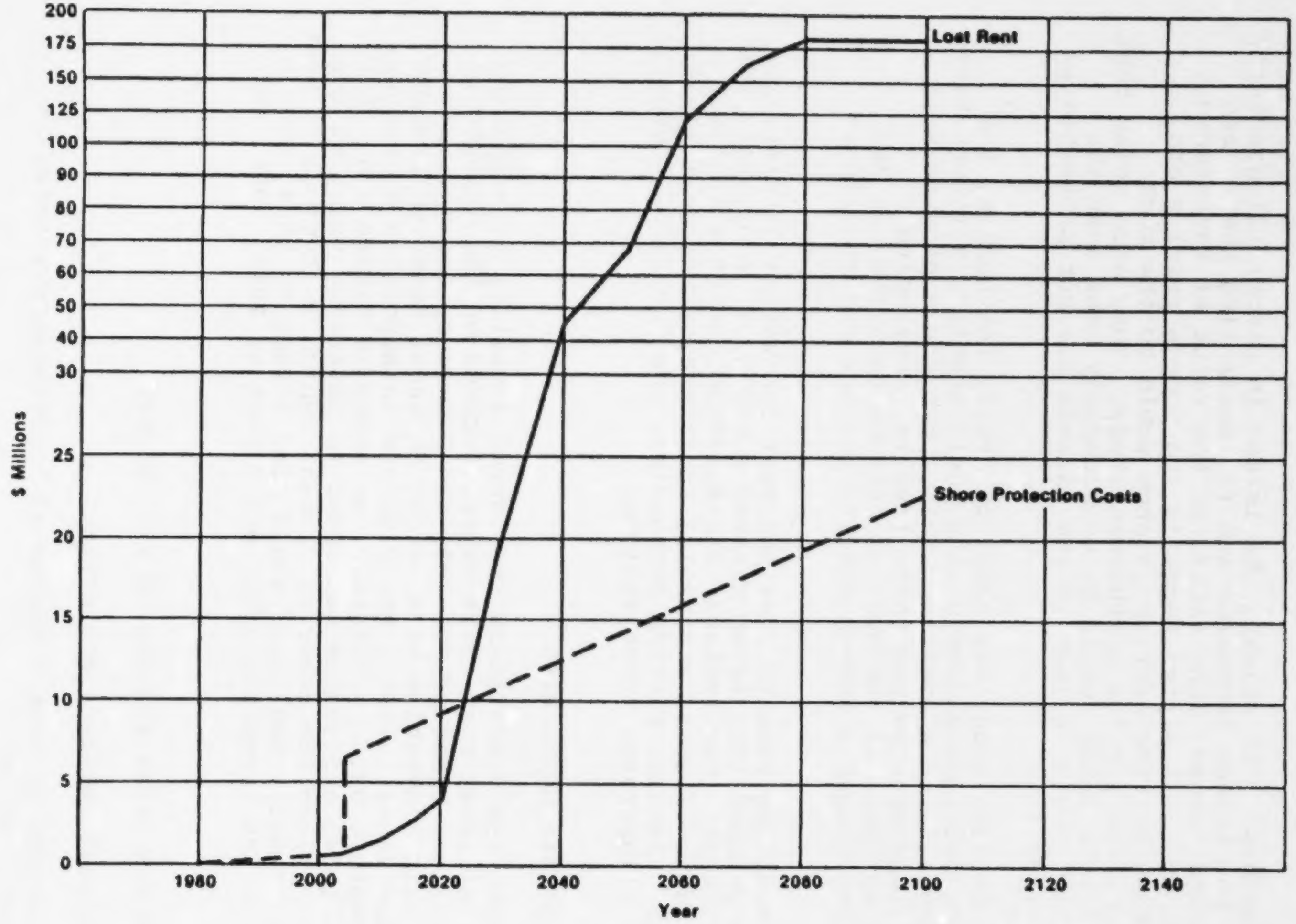


Figure 9-6. Annual Cost of Raising Island Versus Annual Costs (Lost Rent) From Not Protecting the Island

Source: Titus and Greene, Volume __.

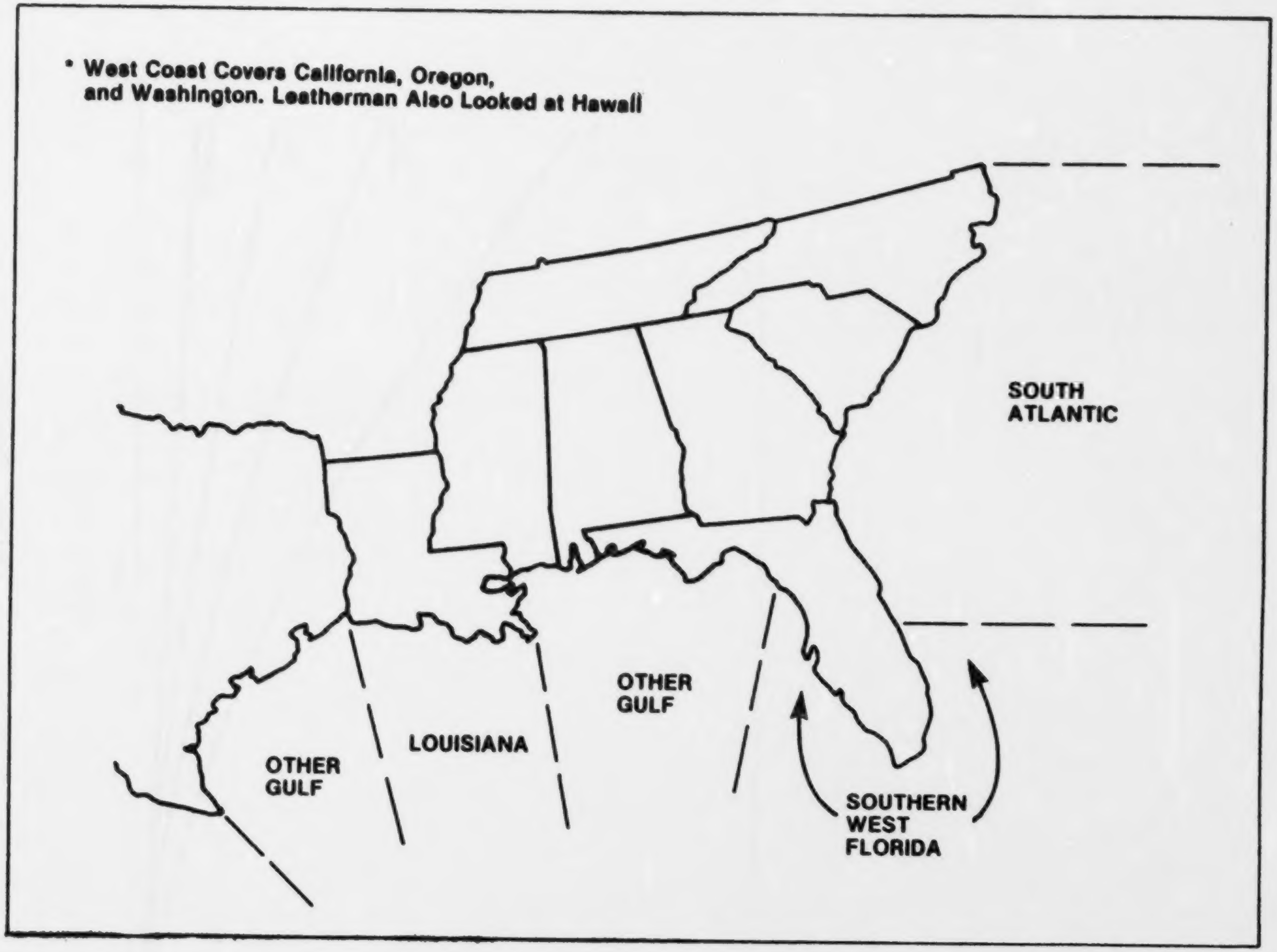

* West Coast Covers California, Oregon, and Washington. Leatherman Also Looked at Hawaii
SOUTH ATLANTIC
OTHER GULF
LOUISIANA
OTHER GULF
SOUTHERN WEST FLORIDA

Figure 9-7. Coastal Regions Used In This Study

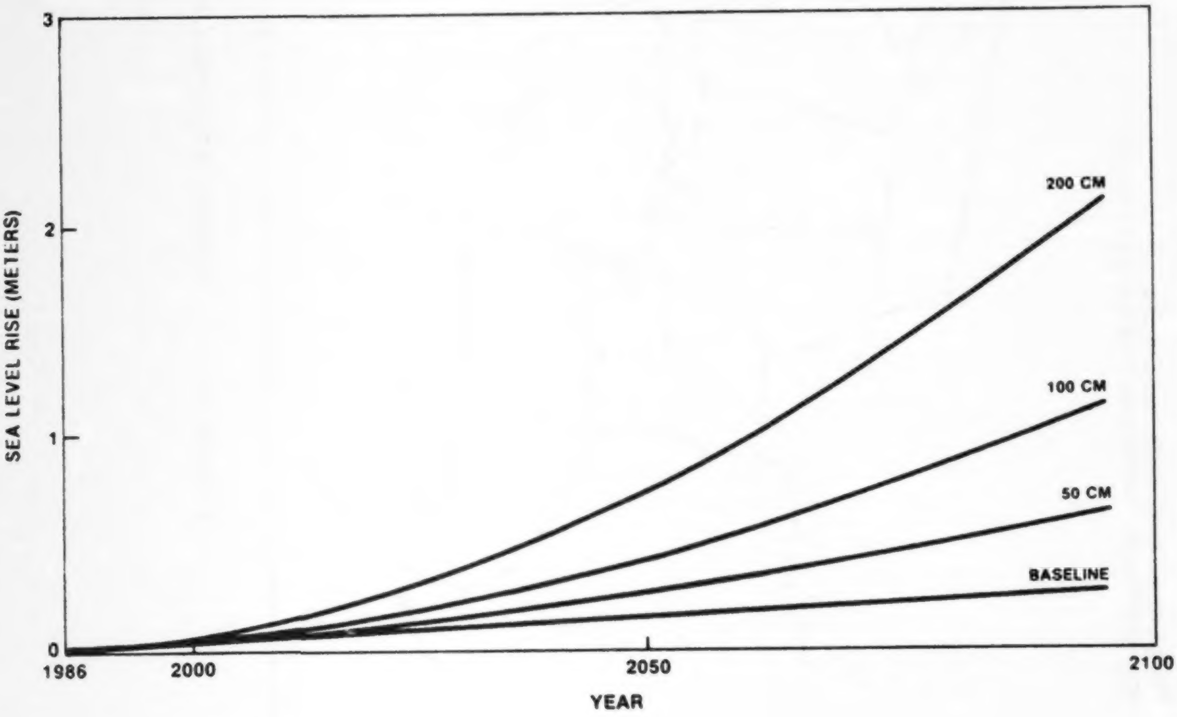


Figure 9-8. Sea Level Scenarios (Miami Beach)

- A rise in sea level greater than the rate of vertical wetland accretion would result in a net loss of coastal wetlands.
- The loss of wetlands would be greatest if all developed areas are protected, less if shorelines retreat naturally, and least if barrier islands are protected while mainland shores retreat naturally.
- The loss of coastal wetlands would be greatest in the Southeast, particularly Louisiana.

Study Design

Park's study was based on a sample of 46 coastal sites that were selected at regular intervals. This guaranteed that particular regions would be represented in proportion to their total area in the coastal zone. The sites chosen accounted for 10% of the U.S. coastal zone.

To estimate the potential loss of wet and dry land, Park first had to characterize their elevations. For wetlands, he used satellite imagery to determine plant species for 60- by 80-m parcels. Using estimates from the literature on the frequency of flooding that can be tolerated by various wetland plants, Park determined the percentage of time particular parcels currently under water. From this, Park inferred wet land elevation based on the known tidal range. For dry land, Park used spot elevation measurements to interpolate between contours on U.S. Geological Survey topographic maps.

Park estimated the loss of wetlands and dryland for no protection, protection of developed areas, and protection of all shores. For the no-protection scenario, estimating the loss of dryland is straightforward. However, for calculating wetland loss, Park used published vertical accretion rates (see Armentano et al., 1988). For accelerated sea level rise, he allowed for some acceleration of vertical accretion in areas with ample supplies of sediment, such as tidal deltas.

For sites in the Southeast, Park also allowed for the gradual replacement of salt marshes by mangrove swamps. The upper limit for mangroves is around Fort Lauderdale. Park used the GISS transient scenario to determine the year particular sites would be as warm as Fort Lauderdale is today and assumed that mangroves would begin to replace marsh after that year.

Limitations

The greatest uncertainty in Park's analysis is a poor understanding of the potential rates of vertical accretion. Although this could substantially affect the results for low sea level rise scenarios, the practical significance is small for a rise of 1 m because it is generally recognized that wetlands could not keep pace with the rise of 1 to 2 cm/year that such a scenario implies for the second half of the 21st century.

Errors can be made when determining vegetation type based on the use of infrared "signatures" that satellites receive. Park noted, for example, that in California the redwoods have a signature similar to marsh grass. For only a few sites Park was able to corroborate his estimates of vegetation type.

Park's study did not consider the potential implications of alternative methods of managing riverflow. This limitation is particularly serious regarding application to Louisiana, where widely varying measures have been proposed to increase the amount of water and sediment delivered to the wetlands. Finally, the study makes no attempt to predict which undeveloped areas might be developed in the next century.

At the coarse (500-m) scale Park used, the assumption of only protecting developed areas amounts to not protecting a number of mainland areas where the shoreline is developed but areas behind the shoreline are not. Therefore, Park's estimates for protecting developed areas should be interpreted as applying to the case where only densely developed areas are protected.

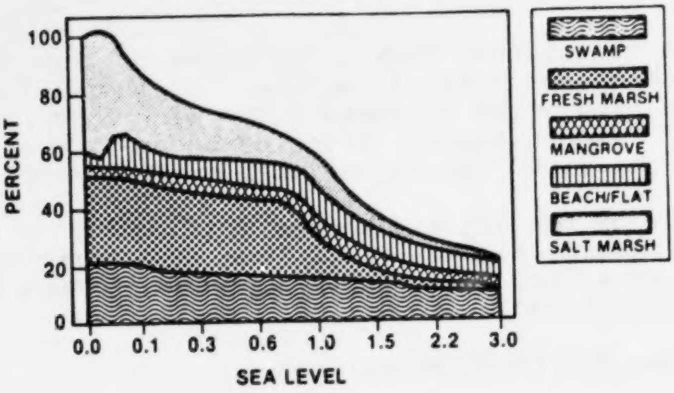
Results

Park's results supported the hypotheses suggested by previous studies. Figure 9-9 shows nationwide wetland loss for various (0- to 3-m) sea level rises for the three policy options investigated. For a 1-m rise, 66% of all coastal wetlands would be lost if all shorelines were protected, 49% would be lost if only developed areas were protected, and 46% would be lost if shorelines retreated naturally.

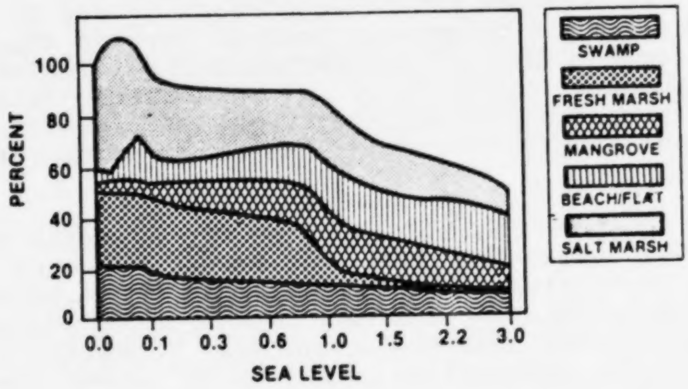
As expected, the greatest losses of wetlands would be in the Southeast, which currently contains 85% of U.S. coastal wetlands (Figure 9-9). For a 1-m sea level rise, 6,000-8,600 mi^2 (depending on which policy is implemented) of U.S. wetlands would be lost; 90-95% of these would be in the Southeast, and 40-50% would be in Louisiana alone. By contrast, neither the Northeast nor the West would lose more than 10% of its wetlands if only currently developed areas are protected.

COMPOSITE FOR UNITED STATES

A. 3 m ALL DRY LAND PROTECTED



B. 3 m DEVELOPED AREAS PROTECTED



C. 3 m UNPROTECTED

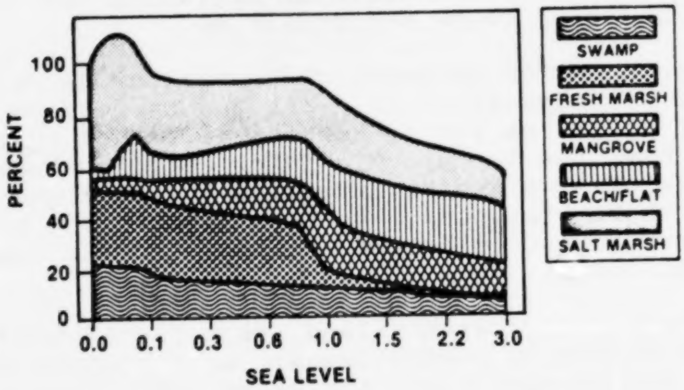


Figure 9-9. Nationwide Wetland Loss for Three Shoreline-Protection Options

Source: Park, Volume __.

Figure 9-10 illustrates Park's estimates of the inundation of dryland for the seven coastal regions. If shorelines retreat naturally, a 1-m rise would inundate 7,700 mi^2 of dryland, an area the size of Massachusetts. Rises of 50 and 200 cm would result in losses of 5,000 and 12,000 mi^2, respectively.

Approximately 70% of the dryland losses would occur in the Southeast, particularly Florida, Louisiana, and North Carolina. The eastern shores of the Chesapeake and Delaware Bays also would lose considerable acreage.

Costs of Defending Sheltered Shorelines

Study Design

This study began by examining Long Beach Island in depth. This site and five other sites were used to develop engineering rules of thumb for the cost of protecting coastal lowlands from inundation. Examining the costs of raising barrier islands required an assessment of two alternatives: (1) building a levee around the island; and (2) allowing the island to migrate landward.

After visiting Long Beach Island and the adjacent mainland, Weggel designed and estimated costs for an encirclement scheme consisting of a levee around the island and a drainage system that included pumping and underground retention of stormwater. For island migration, he used the Bruun Rule to estimate oceanside erosion and navigation charts to calculate the amount of sand necessary to fill the bay an equivalent distance landward. For island raising and island migration, Weggel used the literature to estimate the costs of elevating and moving houses and of rebuilding roads and utilities.

Weggel's approach for estimating the nationwide costs was to examine a number of index sites in depth and thereby develop generalized cost estimates for protecting different types of shorelines. He used the topographic information collected by Park for a sample of 95 sites to determine the area and shoreline length that had to be protected. He then applied the cost estimation factors to each site and extrapolated the sample to the entire coast.

After assessing Long Beach Island, Weggel conducted less detailed studies of the following areas: metropolitan New York; Dividing Creek, New Jersey; Miami and Miami Beach; the area around Corpus Christi, Texas; and parts of San Francisco Bay.

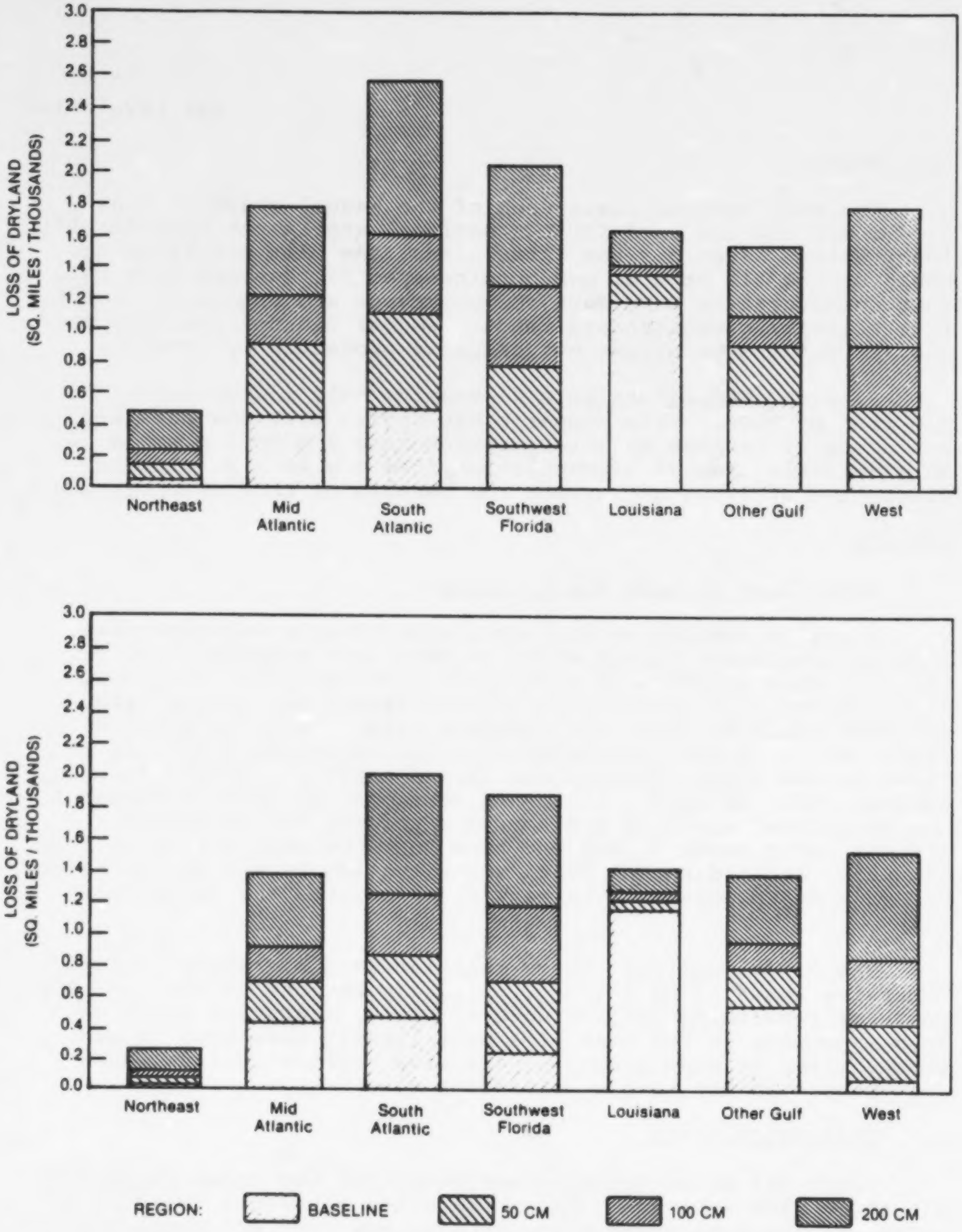


Figure 9-10. Loss of Dry Land by 2100 (a) without protection (b) with protection

Source: Derived from Park, Volume __; (see also Titus and Green, Volume __.)

Limitations

The most serious limitation of the Weggel study is that cruder methods are used for the national assessment than for the index sites. Even for the index sites, the cost estimates are based on the literature, not on site-specific designs that take into consideration wave data for bulkheads and potential savings from tolerating substandard roads. Weggel did not estimate the cost of pumping rainwater out of areas protected by levees.

Finally, Weggel was able to examine only one scenario: a 2-m rise by 2100. This scenario was chosen over the more likely 1-m scenario because an interpolation from 2 m to 1 m would be more reliable than an extrapolation from 1 m to 2 m. (See the discussion of Titus and Greene for results of the interpolation.)

Results

Case Study of Long Beach Island

Weggel's cumulative cost estimates clearly indicate that raising Long Beach Island would be much less expensive ($1.7 billion) than allowing it to migrate landward ($7.7 billion). Although the cost of building a levee around the island ($800 million) would be less, the "present value" would be greater (Table 9-1). Weggel concluded that the levee would have to be built in the 2020s, whereas the island could be raised gradually between 2020 and 2100. Thus, the (discounted) present value of the levee cost would be greater, and raising the necessary capital for a levee at any one time could be more difficult than gradually rebuilding the roads and elevating houses as the island was raised. Moreover, a levee would eliminate the waterfront view.

The Weggel analysis shows that landward migration is more expensive than island raising, primarily because of the increased costs of rebuilding infrastructure. Thus, migration might be less expensive in the case of a very lightly developed island. Levees might be more practical for wide barrier islands where most people do not have a waterfront view.

Nationwide Costs

Table 9-2 shows Weggel's estimates for the index sites and his nationwide estimate. The index sites represent two distinct patterns. Because urban areas such as New York and Miami would be entirely protected by levees, the cost of moving buildings and rebuilding roads and utilities would be relatively small. On the other hand, Weggel concluded that in more rural areas such as Dividing Creek, New Jersey, only the pockets of development would

Table 9-1. Total Cost of Protecting Long Beach Island From a 2-m Rise in Sea Level (millions of dollars)

Protective Measure	Encirclement	Island Raising	Island Migration
Sand Costs:			
Beach	290	290	0
Land creation/maintenance	NA	270	321
Moving/elevating houses	NA	74	37
Roads/utilities	0	1072	7352
Levee and drainage	542	0	0
Total	832	1706	7710

NA = Not applicable.

Source: Leatherman, Weggel.

Table 9-2. Cumulative Cost of Protecting Sheltered Waters (millions of 1986 dollars)

	New Bulkhead	Raise Old Bulkhead	Move Building	Roads/ Utils	Total
Index Sites					
New York	57	205	0.5	9.5	272.3
Long Beach	3	4	2.7	3.8	13.7
Dividing Creek	4	6	4.8	18.2	33.0
Miami area	11	111	0.3	8.3	130.7
Corpus Christi	11	29	2.8	40.9	83.4
San Francisco Bay	3	19	2.0	20.0	44.0
Nationwide Estimate					
	Low		High		
Northeast	6,932		23,607		
Mid-Atlantic	4,354		14,603		
Southeast	9,249		29,883		
West	4,097		12,802		
Nation	24,633		80,176		

Source: Weggel et al.

be protected. The roads that connected them would have to be elevated or replaced with bridges, and the small number of isolated buildings would have to be moved.

Weggel estimates that the nationwide cost of protecting developed shorelines would be $25 billion, assuming bulkheads are built, and $80 billion assuming levees are built. Unlike wetland loss, the cost of protecting developed areas from the sea would be concentrated more in the Northeast than in the Southeast because a much greater portion of the southeastern coast is undeveloped.

Case Study of the Value of Threatened Coastal Property

Study Design

Yohe's objective was to estimate the loss of property that would result from not holding back the sea. Using estimates of erosion and inundation for Long Beach Island from Leatherman and Park et al., Yohe determined which land would be lost from sea level rise for a sample of strips spanning the island from the ocean to the bay. He then used the Ocean County, New Jersey, tax assessor's estimates of the value of the land and structures that would be lost, assuming that the premium associated with a view of the bay or ocean would be transferred to another property owner and not lost to the community. He estimated the annual stream of rents that would be lost by assuming that the required return on real estate is 10% after tax. Yohe assumed that a property on the bay side was "lost" whenever it was flooded at high tide, and that property on the ocean side was "lost" when the house was within 40 feet of the spring high tide mark. (See Titus and Greene, Volume x for discussion.)

Limitations

Yohe's results for a sea level rise of less than 18 inches are sensitive to the assumption regarding when a property would be lost. On the bay side, people might learn to tolerate tidal inundation. Unless a major storm occurred, people could probably occupy oceanfront houses until they were flooded at high tide. However, the resulting loss of recreational use of the beach probably would have a greater impact than abandoning the structure. Tax maps do not always provide up-to-date estimates of property values. However, the distinction between the tax assessor's most recent estimate of market value and the current market value is small compared with the possible changes in property values that will occur over the next century; hence, Titus and Greene used tax assessors estimates of market values.

Results

Yohe's results suggest that the cost of gradually raising Long Beach Island would be far less than the value of the resources that would be protected. Figure 9-6 compares Yohe's estimates of the annual loss in rents resulting from not holding back the sea with Weggel's estimates of the annual cost of raising the island for the 2-m scenario. With the exception of the 2020s, the annual loss in rents resulting from not holding back the sea would be far less than the annual costs of pumping sand and elevating structures.

Nationwide Cost of Pumping Sand Onto Recreational Beaches

Leatherman's goal was to estimate the cost of defending the U.S. ocean coast from a rise in sea level.

Study Design

Owing to time constraints, it was possible to consider only one technology. Based on the Long Beach Island results, Leatherman assumed that the cost of elevating recreational beaches and coastal barrier islands by pumping in offshore sand would provide a more representative cost estimate than assuming that barrier islands would be abandoned, migrate landward, or be encircled with dikes and levees.

The first step in Leatherman's analysis was to estimate the area of (1) the beach system, (2) the low bayside, and (3) the slightly elevated oceanside of the island. Given the areas, the volume of sand was estimated by assuming that the beach system would be raised by the amount of sea level rise. The bay and ocean sides of the island would not be raised until after a rise in sea level of 1 and 3 feet, respectively. Cost estimates for the sand were derived from inventories conducted by the U.S. Army Corps of Engineers.

Leatherman applied this method to all recreational beaches from Delaware Bay to the mouth of the Rio Grande, as well as California, which accounts for 80% of the nation's beaches. He also examined one representative site in each of the remaining States.

Limitations

Although the samples of sites in the Northeast and Northwest are representative, complete coverage would have been more accurate. Furthermore, Leatherman used conservative assumptions in estimating the unit costs of sand. Generally, a fraction of the sand placed on a beach washes away because the sand's grain is too small. Moreover, as dredges have to move further offshore to find sand, costs will increase.

For Florida, Leatherman used published estimates of the percentage of fine-grain sand and assumed that the dredging cost would rise $1 per cubic yard for every additional mile offshore the dredge had to move. For the other States, however, he assumed that the deposits mined would have no fine-grain sand and that dredging costs would not increase. (To test the sensitivity of this assumption, Titus and Greene developed an increasing-cost scenario.) Leatherman assumed no storm worse than the 1-year storm, which underestimates the sand volumes required.

A final limitation of the Leatherman study is that it represents the cost of applying a single technology throughout the ocean coasts of the United States. Undoubtedly, some communities (particularly Galveston and other wide barrier islands in Texas) would choose to erect levees and seawalls or to accept a natural shoreline retreat rather than to pump sand. This approach may overestimate the costs of pumping sand.

Results

Table 9-3 illustrates Leatherman's estimates. A total of 1,900 miles of shoreline would be nourished. Of 746 mi^2 of coastal barrier islands that would be raised for a 4-foot sea level rise, 208 mi^2 would be for a 2-foot rise. As the table shows, two-thirds of the nationwide costs would be borne by four southeastern states: Texas, Louisiana, Florida, and South Carolina.

Figure 9-11 illustrates the cumulative nationwide costs over time. For the 50- and 200-cm scenarios, the cumulative cost would be $2.3-4.4 billion through 2020, $11-20 billion through 2060, and $14-58 billion through 2100. By contrast, if current trends continue, the total cost of sea level rise for beach nourishment would be about $35 million per year.

Synthesis of the Three National Studies

Study Design

Although Weggel used Park's topographic data, the analysis in the three nationwide studies proceeded independently. Titus and Greene's primary objectives were to combine various results to estimate the nationwide cost of holding back the sea for

Table 9-3. Cost of Placing Sand on U.S. Recreational Beaches and Coastal Barrier Islands and Spits

State	Baseline	Sea Level Rise by 2100		
		50 cm	100 cm	200 cm
	($ millions)			
Maine[a]	22.8	119.4	216.8	412.2
New Hampshire[a]	8.1	38.9	73.4	142.0
Massachusetts[a]	168.4	489.5	841.6	1,545.8
Rhode Island[a]	16.3	92.0	160.6	298.2
Connecticut[a]	101.7	516.4	944.1	1,799.5
New York[a]	143.6	769.6	1,373.6	2,581.4
New Jersey[a]	157.6	902.1	1,733.3	3,492.5
Delaware	4.8	33.6	71.1	161.8
Maryland	5.7	34.5	83.3	212.8
Virginia	30.4	200.8	386.5	798.0
North Carolina	137.4	655.7	1,271.2	3,240.4
South Carolina	183.5	1,157.9	2,147.7	4,347.7
Georgia	25.9	153.6	262.6	640.3
Florida (Atlantic coast)	120.1	786.6	1,791.0[b]	7,745.5[b]
Florida (Gulf coast)	149.4	904.3	1,688.4[b]	4,091.6[b]
Alabama	11.0	59.0	105.3	259.6
Mississippi	13.4	71.9	128.3	369.5
Louisiana	1,955.8	2,623.1	3,492.7	5,231.7
Texas	349.6	4,188.3	8,489.7	17,608.3
California	35.7	174.1	324.3	625.7
Oregon[a]	21.9	60.5	152.5	336.3
Washington State[a]	51.6	143.0	360.1	794.4
Hawaii[a]	73.5	337.6	646.9	1,267.5
Nation	3,788.0	14,512.0	26,745.0	58,002.0

[a] Indicates States where estimate was based on extrapolating a representative site to the entire State. All other States have 100% coverage.

[b] Florida estimates account for the percentage of fine-grain sediment, which generally washes away, and for cost escalation as least expensive sand deposits are exhausted. All other estimates conservatively ignore this issue.

Source: Leatherman. (Baseline derived from Leatherman).

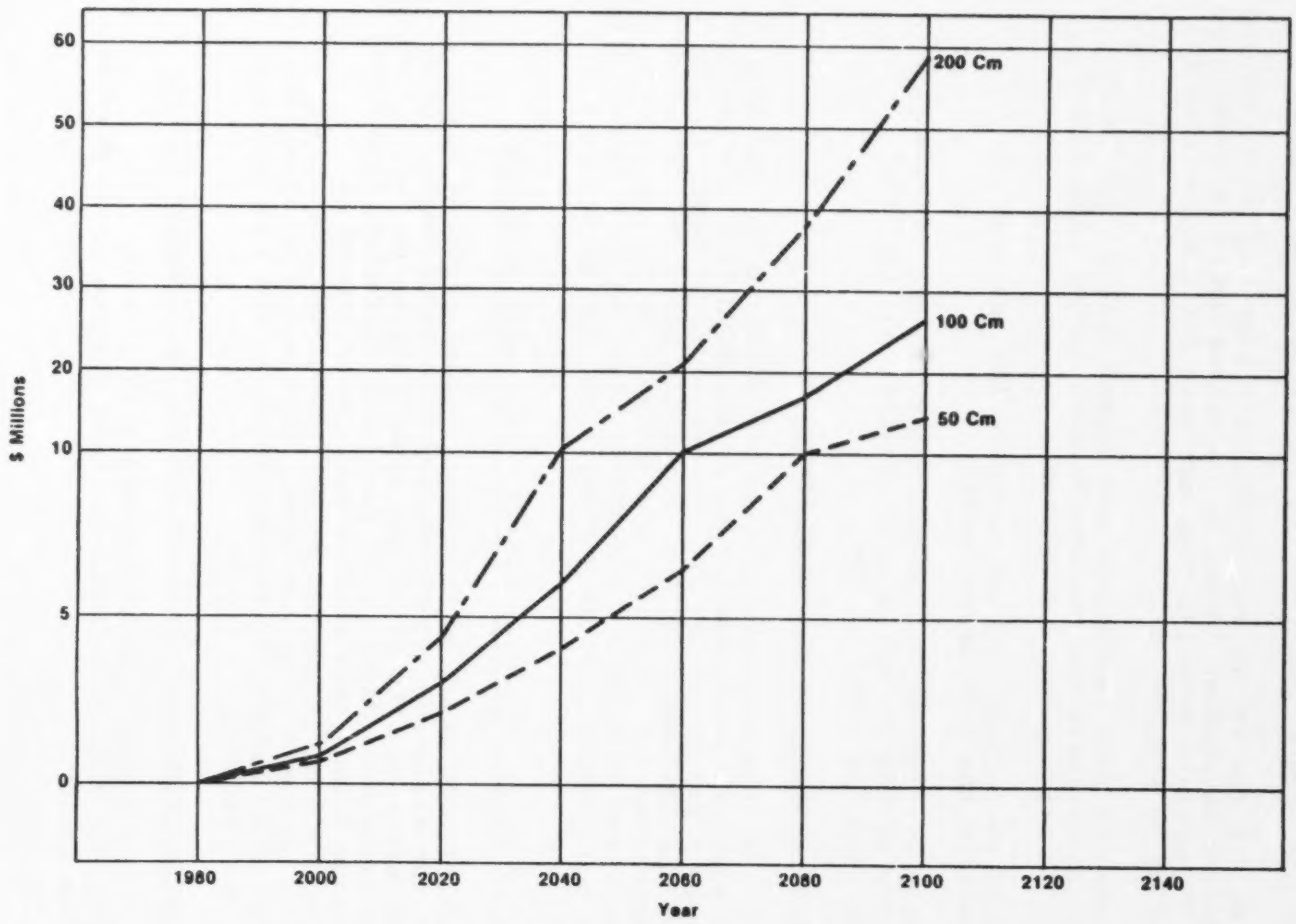


Figure 9-11. Nationwide Cost of Sand for Protecting Ocean Coast

Source: Leatherman, Volume -

various sea level rise scenarios and to derive ranges for the specific impacts.

Titus and Greene undertook the following primary tasks:

1. Use Park's results to weight Weggel's high and low scenarios according to whether levees or bulkheads would be necessary, and interpolate Weggel's cost estimate for the 2-m rise to rises of 50 and 100 cm.

2. Use results from Leatherman and Weggel, along with census data, to estimate the nationwide cost (other than pumping sand) of raising barrier islands.

3. Develop an increasing-cost scenario for the cost of protecting the open ocean coast.

4. Develop statistical confidence intervals for wetland loss, impacts of the various policy options, and costs of protecting developed shores.

Cost of Protecting Sheltered Shores

Titus and Greene developed a single estimate for protecting each site with bulkheads and levees by assuming that the portion of developed areas protected with levees would be equal to the portion of the lowlands that Park estimated would be inundated. They interpolated the resulting 2-m estimate to 50 and 100 cm estimates, based on Weggel's assumption that the cost of building bulkheads and levees rises as a function of the structure's height.

Cost of Raising Barrier Islands Other Than Dredging

Weggel's case study of Long Beach Island provided cost estimates for elevating structures and rebuilding roads, while Leatherman estimated the area that would have to be raised. Many barrier islands have development densities different from those of Long Beach Island because they have large tracts of undeveloped land or larger lot sizes. Therefore, Titus and Greene used census data to estimate a confidence interval for the average building density of barrier islands, and they applied Weggel's cost factors.

Sensitivity of Sand Costs to Increasing Scarcity of Sand

Titus and Greene used Leatherman's escalating cost assumptions for Florida to estimate sand pumping costs for the rest of the nation.

Confidence Intervals

The Park and Weggel studies involved sampling, but the researchers did not calculate statistical confidence intervals. Therefore, Titus and Greene developed 95% confidence intervals for the cost of protecting sheltered coasts, the area of wetland loss for various scenarios.

Limitations

Besides all of the limitations that apply to the Park, Leatherman, and Weggel studies, a number of others apply to Titus and Greene.

Cost of Protecting Sheltered Shores

Titus and Greene assumed that the portion of the coast requiring levees (instead of bulkheads) would be equal to the portion of lowlands that otherwise would be inundated. This assumption tends to understate the need for levees. For example, a community that is 75% high ground often would still have very low land along all of its shoreline and hence would require a levee along 100% of the shore. But Titus and Greene assume that only 25% would be protected by levees.

Cost of Raising Barrier Islands

The data provided by Weggel focused only on elevating roads, buildings, and bulkheads. Thus, Titus and Green do not consider the cost of replacing sewers, water mains, or buried cables. On the other hand, Weggel's cost factors assume that rebuilt roads would be up to engineering standards; it is possible that communities would tolerate substandard roads. In addition, the census data Titus and Greene used were only available for incorporated communities, many of which are part barrier island and part mainland; thus, the data provide only a rough measure of typical road density.

Sensitivity of Sand Costs to Increased Scarcity of Sand

Finally, Titus and Greene made no attempt to determine how realistic their assumption was that sand costs would increase by the same pattern nationwide as they would in Florida.

Results

Loss of Wetlands and Dryland

Table 9-4 illustrates 95% confidence intervals for the nationwide losses of wetlands and dryland. If all shorelines

Table 9-4. Nationwide Loss of Wetlands and Drylands

	Square Miles (%)			
	Baseline	50 cm	100 cm	200cm
Wetlands				
Total protection	N.C.	4944-8077 (38-61)	6503-10843 (50-82)	8653-11843 (66-90)
Standard protection	1168-3341 (9-25)	2591-5934 (20-45)	3813-9068 (29-69)	4350-10995 (33-80)
No protection	N.C.	2216-5592 (17-43)	3388-8703 (26-66)	3758-10025 (29-76)
Drylands				
Total protection	--	0	0	0
Standard protection	--	2180-6147	4136-9186	6438-13496
No protection	--	3315-7311	5123-10330	8791-15394

N.C. = Not Calculated

Source: Titus and Greene, Volume __.

were protected, a 1-m rise would result in a loss of 50-82% of U.S. coastal wetlands, and a 2-m rise would result in a loss of 66-90%. If only the densely developed areas are protected, the losses would be 29-69% and 61-80% for the 1- and 2-m scenarios, respectively. Except for the Northeast, no protection results in only slightly lower wetland loss than protecting only densely developed areas. Although the estimates for the Northeast, mid-Atlantic, the Gulf regions outside Louisiana, and the Florida peninsula are not statistically significant (at the 95% confidence levels), results suggest that wetland loss would be least in the Northeast and Northwest.

Costs of Holding Back the Sea

Table 9-5 illustrates the Titus and Greene estimates of the costs of holding back the sea. The low range for the sand costs is based on Leatherman's study, and the high range is based on the increasing cost scenario Titus and Greene developed. The uncertainty range for the costs of elevating structures reflects the uncertainty in census data regarding the current density of development. High and low estimates for the cost of protecting sheltered shorelines are based on the sampling errors of the estimates for the 46 sites that both Park et al. and Weggel et al. examined.

Titus and Greene estimated that the cumulative nationwide cost of protecting currently developed areas in the face of a 1-m rise would be from $73 to 111 billion, with costs for the 50- and 200-cm scenarios ranging from $32 to 309 billion.

POLICY IMPLICATIONS

Wetland Protection

The nationwide analysis showed that a 50- to 200-cm rise in sea level could reduce the coastal wetland acreage (outside Louisiana) by 17-76% if no mainland areas are protected, by 20-80% if only currently developed areas are protected, and by 38-90% if all mainland areas are protected. These estimates of the areal losses understate the differences in impacts for the various land-use options. Although a substantial loss would occur even with no protection, most of today's wetland shorelines still would have wetlands; the strip simply would be narrower. By contrast, protecting all mainland areas would generally replace natural shorelines with bulkheads and levees. This distinction is important because for many species of fish, the length of a wetland shoreline is more critical than the total area.

Table 9-5. Cumulative Nationwide Cost of Protecting Barrier Islands and Developed Mainland Through the Year 2100 (billions of dollars)

	Sea Level Scenario		
	50 cm	100 cm	200 cm
Open Coast			
Sand	15-20	27-41	58-100
Raise houses, roads, utils	9-13	21-57	75-115
Sheltered shores	5-13	11-33	30-101
Total*	32-43	73-111	119-309

Source: Titus and Greene (Volume ___).

*Note: Range for totals are based on the square root of the sum of squared ranges.

Options for State and Local Governments

Titus (1986) examined three approaches for maintaining wetland shorelines in the face of a rising sea: (1) no further development in lowlands; (2) no action now but a gradual abandonment of lowlands as sea level rises; and (3) allowing future development only with a binding agreement to allow such development to revert to nature if it is threatened by inundation.

The first option would encounter legal or financial hurdles. The extent to which the "due-process" clause of the Constitution would allow governments to prevent development in anticipation of sea level rise has not been specifically addressed by the courts. Although purchases of land would be feasible for parks and refuges, the cost of buying the majority of lowlands would be prohibitive. Moreover, this approach requires preparation for a rise in sea level of a given magnitude; if and when the sea rises beyond that point, the wetlands would be lost. Finally, preventing future development would not solve the loss of wetlands resulting from areas that have already been developed.

Enacting no policy today and addressing the issue as sea level rises would avoid the costs of planning for the wrong amount of sea level rise but would probably result in less wetland protection. People are developing coastal property on the assumption that they can use the land indefinitely. It would be difficult for any level of government to tell property owners that they must abandon their land with only a few years' notice, and the cost of purchasing developed areas would be even greater than the cost of buying undeveloped areas.

Economic theory suggests that under the third alternative, people would develop a property only if the temporary use provided benefits greater than the costs of writing it off early. This approach would result in the greatest degree of flexibility, because it would allow real estate markets to incorporate sea level rise and to determine the most efficient use of land as long as it remains dry.

This approach could be implemented by regulations that prohibit construction of bulkheads as sea level rises or by the use of conditional long-term leases that expire when high tide falls above a property's elevation.

Maine (1987) has implemented this third approach through its coastal dune regulations, which state that people building houses along the shore should assume that they will have to move their houses if their presence prevents the natural migration of coastal wetlands, dunes, or other natural shorelines. A number of States also have regulations that discourage bulkheads, although they do not specifically address sea level rise. The option can be implemented through cooperative arrangements between developers, conservancy groups, and local governments. (See Titus and Greene for additional details.)

The Federal Role

Section 404 of the Clean Water Act discourages development of existing wetlands, but it does not address development of areas that might one day be necessary for wetland migration. This program will provide lasting benefits, even if most coastal wetlands are inundated. Although marshes and swamps would be inundated, the shallow waters that formed could provide habitat for fish and submerged aquatic vegetation. No one has assessed the need for a Federal program to protect wetlands in the face of rising sea level.

Coastal Protection

State and Local Efforts

State and local governments currently decide which areas would be protected and which would be allowed to erode. Currently, few localities contribute more than 10% of the cost of beach nourishment, with the States taking on an increasing share from the Federal Government. However, if global warming increases the costs of coastal protection over the next century by $50-300 billion, many coastal officials doubt that their States could raise the necessary funds. If State funds could not be found, the communities themselves would have to take on the necessary expenditures or adapt to erosion.

Long Beach Island, New Jersey, illustrates the potential difficulties. The annual cost of raising the island would average $200-1,000 per house over the next century (Titus and Greene, Volume __1). Although this amount is less than one week's rent during the summer, it would more than double property taxes, an action that is difficult for local governments to contemplate. Moreover, the island is divided among six jurisdictions, all of which would have to participate.

More lightly developed communities may decide that the benefits of holding back the sea are not worthwhile. Sand costs would be much less for an island that migrated. Although Weggel estimated that higher costs would be associated with allowing Long Beach Island to migrate landward than with raising the island in place, this conclusion resulted largely from the cost of rebuilding sewers and other utilities that would still be useful if the island were raised.

Regardless of how a barrier island community intends to respond to sea level rise, the eventual costs can be reduced by deciding on a response well in advance. The cost of raising an island can be reduced if roads and utilities are routinely elevated or if they have to be rebuilt for other reasons (e.g., Titus et al., 1987). The cost of a landward migration also can be reduced by discouraging reconstruction of oceanfront houses destroyed by storms (Titus et al., 1984a). The ability to fund the required measures also would be increased by fostering the necessary public debate well before the funds are needed.

Federal Efforts

While State governments generally are responsible for protecting recreational beaches, the U.S. Army Corps of Engineers is responsible for several major Federal projects to rebuild beaches and for efforts to curtail land loss in Louisiana. The long-term success of these efforts would be improved if the Corps were authorized to develop comprehensive long-term plans to address the impacts of sea level rise.

Beach Erosion

In its erosion-control efforts, the Corps has recently shifted its focus from hard structures (e.g., seawalls, bulkheads, and groins) to soft approaches, such as pumping sand onto beaches. This shift is consistent with the implications of sea level rise: groins and seawalls will not prevent loss of beaches due to sea level rise. Although more sand will have to be pumped than current analyses suggest, this approach clearly could ensure the survival of the nation's beaches.

Nevertheless, consideration of accelerated sea level rise would change the cost-benefit ratios of many Corps erosion control projects. As with the operations of reservoirs (discussed in Chapter 6: Southeast), the Corps is authorized to consider flood protection but not recreation. When they evaluated the benefits of erosion control at Ocean City, Maryland, the Corps concluded that less than 10% of the benefits would be for flood control (most were related to recreation). Had they considered accelerated sea level rise, however, the estimated flood protection benefits from having a protective beach would have constituted a considerably higher fraction of the total benefits (Titus, 1985).

Wetland Loss in Louisiana

By preventing freshwater and sediment from reaching the coastal wetlands, Federal management of the Mississippi River is increasing the vulnerability of coastal Louisiana to a sea level rise (e.g., Houck, 1983). For example, current navigation routes require the Corps of Engineers to limit the amount of water flowing through the Atchafalaya River and to close natural breaches in the main channel of the Mississippi; these actions limit the amount of freshwater and sediment reaching the wetlands. Alternative routes have been proposed that would enable water and sediment to reach the wetlands (Louisiana Wetland Protection Panel, 1987). These include dredging additional canals parallel to the existing Mississippi River gulf outlet or constructing a deepwater port east of the city.

Either of these options would cost a few billion dollars. By contrast, annual resources for correcting land loss in Louisiana have been in the tens of millions of dollars. As a result, mitigation activities have focused on freshwater diversion structures and on other strategies that can reduce current wetland loss attributable to high salinities but that would not substantially reduce wetland loss if sea level rises 50-200 cm (Louisiana Wetland Protection Panel, 1987).

The prospect of even a 50 cm rise in sea level suggests the solving the Louisiana wetland loss problem is much more urgent than is commonly assumed. Because federal activities are now a major cause of land loss, and would have to be modified to enable wetlands to survive a rising sea, the problem is unlikely to be solved without a Congressional mandate. A recent interagency report concluded that "no one has systematically determined what must be done to save 10, 25, or 50 percent of Louisiana's coastal ecosystem." (Louisiana Wetland Protection Panel, 1988). Until someone estimates the costs and likely results of strategies with a chance of protecting a significant fraction of the wetlands in face of rising sea level, it will be difficult for Congress to devise a long-term solution.

Flood Insurance

In 1968, Congress created the National Flood Insurance Program with the objective of reducing Federal disaster relief resulting from floods. The Federal Emergency Management Agency (FEMA), which already was responsible for administering disaster relief, was placed in charge of this program as well.

The National Flood Insurance Program sought to offer localities an incentive to prevent flood-prone construction. In return for requiring that any construction in a floodplain be designed to withstand a 100-year flood, the federal government would provide subsidized insurance to existing homes and a fair-market rate for any new construction (which was itself a benefit, since private insurers generally did not offer flood insurance). Moreover, as long as a community joined the program, it would continue to be eligible for federal disaster relief; if it did not join, it would no longer be eligible. As a result of this program, new coastal houses are generally elevated on pilings.

Although Congress intended to prevent coastal disasters, the National Flood Insurance Act does not require strategic assessments of long-term issues (see Riebsame, Volume _). Thus, FEMA has not conducted strategic assessments of how the program could be managed to minimize flood damage from shoreline retreat caused by both present and future rates of sea level rise.

Congress recently enacted the Upton-Jones Amendment (Public Housing Act of 1988), which commits the federal government to pay for rebuilding or relocating houses that are about to erode into the sea. Although the cost of this provision is modest today, a sea level rise could commit the federal Government to purchase the houses on all barrier islands that did not choose to hold back the sea. Furthermore, this commitment could increase the number of communities that decided not to hold back the sea.

The planned implementation of actuarially sound insurance rates would ensure that as sea level rise increased property risk, insurance rates would rise to reflect the risk. This would discourage construction of vulnerable houses, unless their value was great enough to outweigh the likely damages from floods. However, statutes limiting the rate at which flood insurance rates can increase could keep rates from rising as rapidly as the risk of flooding, thereby increasing the federal subsidy.

No assessment of the impacts of sea level rise on the federal flood insurance program has been undertaken.

Sewers and Drains

Sea level rise also would have important impacts on coastal sewage and drainage systems. Wilcoxen (1986) examined the implications of the failure to consider accelerated sea level rise in the design of San Francisco's West Side (sewerage) Transport, a large steel-reinforced concrete box buried under the city's ocean beach. He found that beach erosion will gradually expose the transport to the ocean. Although the structure probably could withstand wave attack, it would act as a seawall and eventually result in loss of the recreational beach or necessitate shore-protection projects that, over the course of a century, would cost more than the project itself. Wilcoxen concludes that had sea level rise been considered, the project probably would have been sited elsewhere.

The impacts of sea level rise on the construction grants program probably would be less in most other cases. As sea level rises, larger pumps would be necessary to transport effluents from settling ponds to the adjacent body of water. However, sea level rise would not necessarily require alternative siting. The projects serving barrier islands often are located on the mainland, and projects located on barrier islands are generally elevated well above flood levels. If barrier islands are raised in response to sea level as the nationwide analysis suggests, sewerage treatment plants will be a small part of the infrastructure that has to be modified.

Engineering assessments have concluded that it is already cost-beneficial to consider sea level rise in the construction of coastal drainage systems in urban areas. For example, the extra cost of installing the larger pipes necessary to accommodate a 1-foot rise in sea level would add less than 10% to the cost of rebuilding a drainage system in Charleston, South Carolina; however, failure to consider sea level rise would require premature rebuilding of the $4 million system (Titus et al., 1987).

RESEARCH NEEDS

A much better understanding of erosion processes is needed 1) to understand how much erosion will take place if no action is taken; and 2) to help identify the most cost-effective means for protecting sandy shores. An improved understanding of how wetland accretion responds to different temperatures, higher CO_2 concentrations, changing mineral content, and the drowning of adjacent wetlands is needed. This will refine our ability to project future wetland loss and, perhaps, devise measures for artificially enhancing their vertical growth.

This report did not examine the impacts of increased flooding because flood models have not been applied to the large numbers of coastal sites that would be necessary to conduct a nationwide assessment. Time dependant estuarine salinity models, such as that of the Delaware River Basin Commission should be applied to major estuaries for examining impacts on ecosystems and drinking water supplies.

Assessments of the impacts of global warming on coastal environments would be greatly improved by better estimates of future sea level rise. In addition to the improved ocean modelling that will be necessary for better projections of surface air temperatures (see Chapter 2: Global Climate Change), this will also require a substantial increase in the resources allocated for monitoring and modelling glacial processes. Finally, this report assumed that winds, waves, and storms remained constant; future studies will need estimates of the changes in these climatic variables.

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DRAFT

CHAPTER 10

AGRICULTURE

FINDINGS

Although climate change is not likely to threaten U.S. food supplies, it will affect crop yields and result in a northward shift in cultivated land, causing significant regional dislocations in agriculture with associated impacts on regional economies. It will expand crop irrigation requirements, stress livestock production, and increase infestations of agricultural pests and diseases.

Crop Yields

o The effects of climate change alone may reduce average yields of corn, soybeans, and wheat, both rainfed and irrigated, except in the northernmost latitudes where warmer conditions provide a longer frost-free growing season. Decreases in modeled yields result primarily from higher temperatures, which shorten a crop's life cycle.

o When the direct effects of CO_2 on crop photosynthesis and transpiration are approximated along with the effects of climate change, average rainfed and irrigated corn, soybeans, and wheat yields could overcome the negative effects of climate change in some locations. If climate changes are severe, yields could decline. Whether these modeled results will be reproduced under field conditions is uncertain.

o Even if the patterns of climate variability are unchanged, yield stability may decrease, particularly under rainfed conditions. This may occur because there would be more days above temperature thresholds for particular crops. The exact magnitude of change will be sensitive to changes in climatic variability.

Economic Impacts

o There may be a small to moderate aggregate reduction in the nation's agricultural output. Production appears to be adequate to meet domestic consumption needs.

o Assuming no change in export demand, reduced outputs would decrease exports, which could negatively affect global food supplies and the U.S. trade balance. This report did not analyze global changes in agriculture.

- Under the most severe climate change scenarios, continued technological improvements, similar to those in recent years, would have to be sustained to offset losses.

- The economic response of agriculture to shifts in regional productivity may be to shift crop production and associated infrastructure in a northward direction. It is not possible to determine if corn and soybean production could be sustained in northern areas, because soil conditions and other factors were not analyzed.

Irrigation Demand

- The demand for irrigated acreage is likely to increase in all regions. This is due to the reliability of irrigated yields relative to dryland yields and to higher commodity prices that make expansion of irrigated production more economically feasible. This result is sensitive to whether the cost of water to farmers increases.

- More irrigation may increase stress on and competition for regional water supplies. Increased irrigation also implies associated increases in surface and groundwater pollution and other forms of environmental degradation.

Agricultural Pests

- Climate warming could change the ranges and populations of agricultural pests. Temperature increases may enhance the survival of insect pests in the winter, extend their northward ranges, increase pest species with more than one generation per year, and allow pest establishment earlier in the growing season. These effects could result in a substantial rise in pesticide use, with accompanying environmental hazards.

Farm-Level Adjustments

- Farmers may adjust to climate change by using full-season and heat-resistant crop species or varieties, by altering planting dates, by planting two crops during one growing season, by increasing or altering their scheduling of irrigation, by using more pesticides, and by harvesting earlier. If climate change is not severe, these adjustments may mitigate losses in crop yields; more severe climate change is likely to make major adaptation necessary.

Livestock Effects

- Higher temperatures may increase disease and heat stress on livestock in some regions. Existing livestock diseases may shift north, while tropical diseases may extend their ranges into southern regions of the United States. Cold stress conditions may be reduced in the winter, but heat stress is likely to increase in the summer. Reproductive capabilities may also decrease.

Policy Implications

- Global climate change has important implications for all parts of the agriculture system. The agricultural research structure, which is dedicated to maintaining U.S. farm productivity, should enhance climate change research from the field level to the national policy level.

- Current U.S. Department of Agriculture (USDA) research on heat- and drought-tolerant crops and practices should be sustained and, possibly, enhanced to limit vulnerability to future climate change.

- The USDA should evaluate the implications of current legislation on the ability of agriculture to adapt to global warming by shifting the types of crops and location of farming. Such adaptation strategies should consider the impacts of soil erosion and water quality.

- The USDA, the Department of Commerce, the U.S. Trade Representative, and the State Department should consider the implications of potential long-term changes in the level of U.S. crop exports for the U.S. balance of trade and strategic interests.

- There is an urgent need for a national drought policy to coordinate Federal response to the possibility of increased frequency and duration of future droughts. Even without climate change, such a policy is needed not only for the agricultural sector, but also for other sectors.

SENSITIVITY OF AGRICULTURE TO CHANGES IN CLIMATE

Agriculture is a critical American industry, providing food for the nation's population and as much as $42.6 billion in exports for the nation's trade balance (Figure 10-1). The industry employs 21 million people -- more than other industry, when taking into account workers on farms and in the meat,

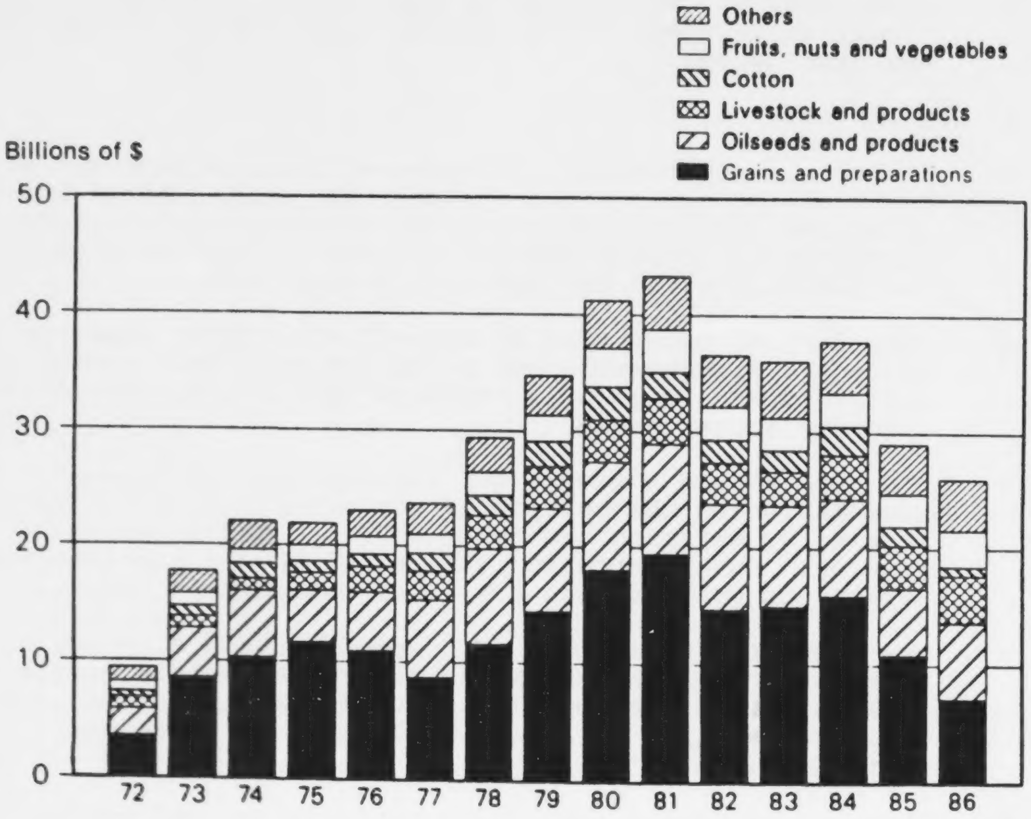

Figure 10-1. Value of U.S. agricultural exports by commodity.

Sources: The World Food Institute and U.S. Department of Agriculture, Economic Research Service, Foreign Agricultural Trade of the United States (Washington, DC), January-February 1987 and various other issues. Livestock excludes poultry and dairy products.

poultry, dairy, baking, and food processing industries (Council for Agricultural Science and Technology, 1988). The U.S. agricultural production system includes farm equipment manufacture, fertilizer and seed supplies, rural banking, and shipping. Total farm assets were $771 billion in 1985; food and fiber were 17.5% of the total gross national product in the same year. Wheat, corn, soybeans, cotton, fruits and vegetables, and livestock are among the most important U.S. agricultural commodities.

The study areas are major agricultural production regions (see Table 10-1). The Great Lakes and Southeastern States are major corn and soybean producers, while the Great Plains States grow mainly wheat and corn.

Worldwide, agricultural products must provide sustenance for the world's growing population, now estimated at about 5 billion and projected to rise to 8.2 billion by 2025 (World Bank, 1988). Global production and consumption of grain have grown steadily since 1960, although regional food shortages continue to occur due to climate variability and socioeconomic factors. Technological advances, such as improved hybrids and irrigation systems, have reduced the dependence of crop yields on the natural environment, but weather is still an important factor in agricultural productivity.

For example, during the Dust Bowl years of the 1930s, wheat and corn yields dropped by up to 50%. Midsummer 1983 saw an unpredicted drought in the U.S. Corn Belt and in the southeastern United States, causing the U.S. corn yields to fall by about a third, from over 7,000 kg/hectare (ha) to about 5,000 kg/ha. And failure of the monsoon season caused shortfalls in crop production in India, Bangladesh, and Pakistan in 1987. The 1980s have also seen the continued deterioration of food production in Africa, despite adequate world food supplies elsewhere, because of persistent drought, internal wars, poor distribution, weak infrastructure, and a deteriorating environment.

The 1988 drought demonstrated the impact that climate variability can have on agricultural productivity. This drought is expected to decrease corn yields by about 40%, and the cost of the 1988 Drought Relief Bill is estimated to be $3.9 billion (New York Times, 1988). The 1988 drought emphasizes anew the close link between agriculture and climate and the need to consider broadly the impacts of potential climate change on U.S. agriculture.

Future changes in climate due to increasing atmospheric trace gases, particularly CO_2, will affect agriculture because

Table 10-1. Crop Data by Region

	Corn	Wheat	Soybeans	Harvested Acres (thousands)
EPA Study Areas				
Southeast	311	272	306	29
Great Lakes	4,644	297	822	92
Great Plains	921	755	136	71
California	38	63	0.01	6
Total (48 States)	8,209	2,507	199	337

Units: Corn, wheat, and soybeans are in thousands of bushels; harvested acres are also in thousands.

Source: 1982 Census of Agriculture, Vol. 1, Geographical Area Series, Part 51, United States Summary and State Data. U.S. Department of Commerce, Bureau of the Census.

light from the sun, frost-free growing seasons, and the hydrologic cycle largely govern crop productivity. Livestock production will also respond to climate change through differing levels of heat and cold stress and altered ranges of disease-carrying vectors such as mosquitoes and ticks. Sea level rise, an associated impact of climate change, will threaten low-lying coastal agricultural regions with seasonal, and in some instances permanent, flooding, saltwater intrusion of freshwater aquifers and rivers, and salt contamination of soils. (See Water Resources chapter in this volume for linkages with agriculture.)

As predicted rises in temperature and other changes in climate variables such as precipitation occur, the higher levels of CO_2 in the air will also affect crops. Increasing CO_2 has boosted crop photosynthesis and has reduced the use of water by crops in experimental settings. Because experimental research has rarely dealt with both the climatic and the direct effects of CO_2 on plants simultaneously, it is difficult to assess the relative contributions of CO_2 and increased temperature to plant responses. This remains one of the most crucial questions in the analysis of impacts of climate change and increased CO_2 on agriculture.

Associated processes, such as changes in agricultural pests, may also play a role in responses of U.S. agriculture to climate change. The presence and abundance of pests affecting both crops and livestock are highly dependent on climate. The severity of the winter season, wind patterns, and moisture conditions determine in large part where pests will be prevalent. As these conditions change, the patterns, numbers, and types of insects also will change.

Much of U.S. agricultural production takes place under technologically advanced cropping systems that are primarily monocultural. Likewise, livestock production is highly specialized, both technically and geographically, and a high degree of integration exists between grain and livestock production. The economic robustness associated with general, multiple-enterprise farms has long since passed from the scene on any significant scale. Thus, the current vulnerability of our agricultural system to climate change may be greater in some ways than it was in the past.

Climate change and agriculture may affect the natural environment. As regional changes occur in crop and livestock production, these changes in agriculture may increase soil erosion, intensify the demand for water for irrigation, degrade water quality, reduce forested land, and destroy wildlife habitats. Other potential consequences are soil degradation, groundwater overdraft, loss of plant and aquatic communities, and reduced resilience in environmental resources in general. (See the Water Resources and Biological Diversity chapters of this report.)

Climate-driven changes in crop and livestock productivity cause changes in profitability and decisionmaking at the farm level, which in turn lead to shifts in farming systems at the regional level and in export-import supply and demand at the national level. Ultimately, impacts of climate change will reverberate throughout the global food economy, altering global food trade. Changes in U.S. agriculture will thus take place in a global context.

PREVIOUS STUDIES OF THE EFFECTS OF CLIMATE CHANGE AND AGRICULTURE

Relationships between climate and agriculture have been studied intensively for many years. However, relatively few studies have specifically addressed both the climatic and the direct effects that the growth in trace gases will have on agriculture. Even fewer studies have addressed these potential effects in an integrated approach that links both biophysical and economic spheres of analysis.

Most research attention in the United States has focused on the direct effects of CO_2 on crops, supported primarily by the U.S. Department of Energy. These studies are reviewed by Acock and Allen (1985) and Cure (1985) who found an average increase in yields of about 30% and increases in water-use efficiency for crops growing in favorable, current climate conditions between 330 and 660 ppm CO_2. Kimball (1985) and Decker et al. (1985) suggest that the potential effects of CO_2 and/or climate change on agricultural production systems may include shifts in production areas and changes in levels of livestock stresses, water availability, and pest control management.

Integrated approaches to the impacts of climate change on agriculture involving both biophysical and economic processes have been considered in studies by Callaway et al. (1982), the Carbon Dioxide Assessment Committee (1983), Warrick et al. (1986), and the Land Evaluation Group (1987). A benchmark international study on both the agronomic and economic effects of climate change on agriculture was conducted by the International Institute for Applied Systems Analysis (Parry et al., 1988). No study has as yet comprehensively examined the combined effects of climate change and the direct effects of CO_2 on U.S. agriculture.

Chapter 10

CLIMATE CHANGE STUDIES IN THIS REPORT

Structure of and Rationale for the Studies

The agricultural studies in this report involve the following research areas (see Table 10-2): (1) crop growth and yield, (2) regional and national agricultural economics, (3) demand for water for irrigation, (4) water quality, (5) pest-plant interactions, (6) direct effects of CO_2 on crop growth and yield, (7) impacts of extreme events, (8) potential farm-level adjustments, (9) livestock diseases, and (10) agricultural policy. The following studies were performed for this report:

Regional Studies

- Effects of Projected CO_2-Induced Climatic Changes on Irrigation Water Requirements in the Great Plains States -- Allen and Gichuki, Utah State University
- Climate Change Impacts upon Agriculture and Resources: A Case Study of California -- Dudek, Environmental Defense Fund
- Farm-Level Adjustments by Illinois Corn Producers to Climatic Change -- Easterling, Resources for the Future
- Impacts of Climate Change on the Fate of Agricultural Chemicals Across the USA Great Plains and Central Prairie -- Johnson, Cooter, and Sladewski, University of Oklahoma
- Impact of Climate Change on Crop Yield in the Southeastern U.S.A: A Simulation Study -- Peart, Jones, and Curry, University of Florida
- Effects of Global Climate Change on Agriculture: Great Lakes Region -- Ritchie, Baer, and Chou, Michigan State University
- Potential Effects of Climate Change on Agricultural Production in the Great Plains: A Simulation Study -- Rosenzweig, Goddard Space Flight Center/Columbia University

Table 10-2. Agriculture Projects for EPA Report to Congress on the Effects of Climate Change

Projects	Regional Studies				National Study
	California	Southeast	Great Lakes	Great Plains	
Crop Production	X	X	X	X	
Demand for Irrigation Water	X	X	X	X	
Water Quality			X	X	
Pest/Plant Interactions			X		
Farm-Level Management			X		
Regional/National Economics	X	X	X	X	X
Direct Effects of CO2	X	X	X	X	X
Livestock Pests & Diseases					X
Climatic Variability					X
Agricultural Policy					X

National Studies

- The Economic Effects of Climate Change on U.S. Agriculture: A Preliminary Assessment -- Adams, Glyer, and McCarl, Oregon State University
- Analysis of Climate Variability in General Circulation Models -- Mearns, Schneider, Thompson, and McDaniel, National Center for Atmospheric Research
- Direct Effects of Increasing CO_2 on Plants and Their Interactions with Indirect (Climatic) Effects -- Rose
- Potential Effects of Climatic Change on Plant-Pest Interactions -- Stinner, Rodenhouse, Taylor, Hammond, Purrington, McCartney, and Barrett, Ohio Agricultural Research and Development Center
- Agricultural Policies for Climate Changes Induced by Greenhouse Gases -- Schuh, University of Minnesota
- Changing Animal Disease Patterns Induced by the Greenhouse Effect -- Stem, Mertz, Stryker, and Huppi, Tufts University
- Effect of Climatic Warming on Populations of the Horn Fly -- Schmidtmann and Miller, Agricultural Research Service

Production of corn, wheat, and soybeans is critical to the economic well-being of the nation's farmers and the national trade balance. These crops make up about two-thirds of the total U.S. agricultural acreage, and their economic value is equal to that of all other crops combined. These three crops were selected for the modeling studies on the effects of climate change on yields.

The results from the regional studies of crop production (not including California), hydrological predictions from the climate models, and an agricultural economics model were linked in an integrated approach, to enable translation of the estimated yield changes from the crop modeling studies and predicted changes in water availability into economic consequences (see Figure 10-2). Such a coordinated analytical framework is necessary to account for the effects of market forces on the total agricultural sector, including livestock, and

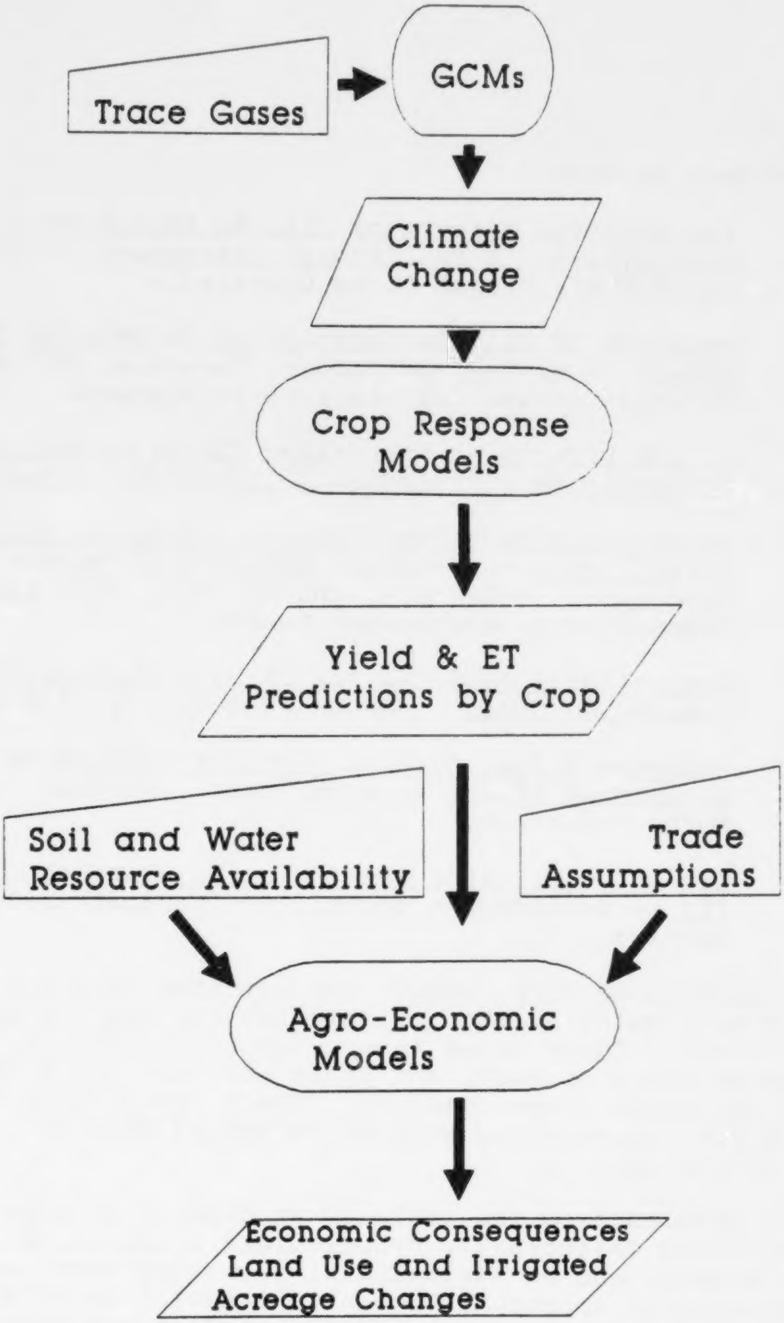
Trace Gases
GCMs
Climate Change
Crop Response Models
Yield & ET Predictions by Crop
Soil and Water Resource Availability
Trade Assumptions
Agro-Economic Models
Economic Consequences Land Use and Irrigated Acreage Changes

Figure 10-2. Flow chart of model interactions in EPA studies of the effects of global climate change on U.S. agriculture.

Source: Dudek (1987).

to evaluate the adequacy of the nation's resource base for agricultural production under climate change. Economic forces may lead farmers to grow more crops in areas with relatively high productivity and fewer crops in areas with relatively low productivity.

The studies of demand for irrigation water, water quality, and farm-level adjustment were also linked with the integrated modeling studies by common assumptions, sites, or outputs. Because California grows a large and diverse number of crop commodities, a simple approach was used to estimate crop yield changes for the California case study based on heat, sunlight, and photosynthetic response to CO_2. These yield changes were then used in a model of agricultural land and water use in California. Several adjustment experiments were included to test possible adaptation mechanisms, such as changes in planting dates and crop varieties.

The agricultural studies performed for this EPA report explore the sensitivities of the different parts of the agricultural system (shown in Table 10-1) to climate change scenarios. They are not meant to be predictions of what will happen; rather, they aim to define ranges and magnitudes of the potential responses as the systems are currently understood.

RESULTS OF AGRICULTURE STUDIES

Regional Crop Modeling Studies

Design of the Studies

Widely validated crop growth models -- CERES-Wheat and CERES-Maize (Ritchie and Otter, 1985) and SOYGRO (Jones et al., 1988) -- were used to simulate wheat, corn, and soybean yields at selected geographically distributed locations within the Great Lakes, the Southeast, and the Great Plains. California crop yield changes were predicted separately by using an agroclimatic index. (See the regional chapters of this report for specific results.) The crop models simulated both dryland and irrigated production systems. The crop modeling approach allowed for analysis of latitudinal gradients in changes in crop yields and provided compatible results for each climate change scenario to be used as input in the agricultural economics study. (See Ritchie et al., Peart et al., and Rosenzweig, Volume _.)

The direct effects of CO_2 -- i.e., increased photosynthesis and improved water-use efficiency -- were included with the climate change scenarios in some model runs to evaluate the combined effects. The direct effects were approximated by computing ratios of elevated CO_2 to ambient CO_2 values for daily photosynthesis and evapotranspiration rates (see Peart et al., Volume _).

Limitations

Uncertainties in the crop modeling studies reside in climate model predictions, locations of the climate stations (not always in production centers), crop growth models, and estimates of the direct effects of CO_2. In particular, the climate change scenarios did not include changes in climate variability, even though changes in the frequencies of extreme events may considerably affect crop yields. Technology and cultivars were assumed not to change from present conditions.

The direct effects of CO_2 in the crop modeling study results may be overestimated for two reasons. First, experimental results from controlled environments may show more positive effects of CO_2 than would actually occur in variable, windy, and pest-infested (weeds, insects, and diseases) field conditions. Second, because other radiatively active trace gases, such as methane (CH_4) also are increasing, the equivalent warming of a doubled CO_2 climate may occur somewhat before an actual doubling of atmospheric CO_2. A level of 660 ppm CO_2 was assumed for the crop modeling experiments, while the CO_2 concentration in 2060 is estimated to be 555 ppm (Hansen et al., 1988).

Results

Climate change scenarios alone, without the direct effects of CO_2, caused simulated yields of corn, soybeans, and wheat to decrease in the Great Lakes, Southeast, and Great Plains regions, except in the northernmost latitudes, where warmer conditions provide a longer frost-free growing season (Figure 10-3). The northern locations where yields increased included sites in Minnesota. Decreases in modeled yields resulted primarily from higher temperatures, which shorten the crop life cycle thus curtailing the production of usable biomass. Dryland modeled yields decreased more than irrigated yields.

When increased photosynthesis and decreased transpiration were included in the crop models along with the climate change scenarios, yields increased over the baseline in some locations but not in others (Figure 10-4). Particularly when combined with the hotter and drier GFDL climate change scenario, the direct effects of CO_2 did not fully compensate for changes in climate variables -- net yields decreased significantly from the base case.

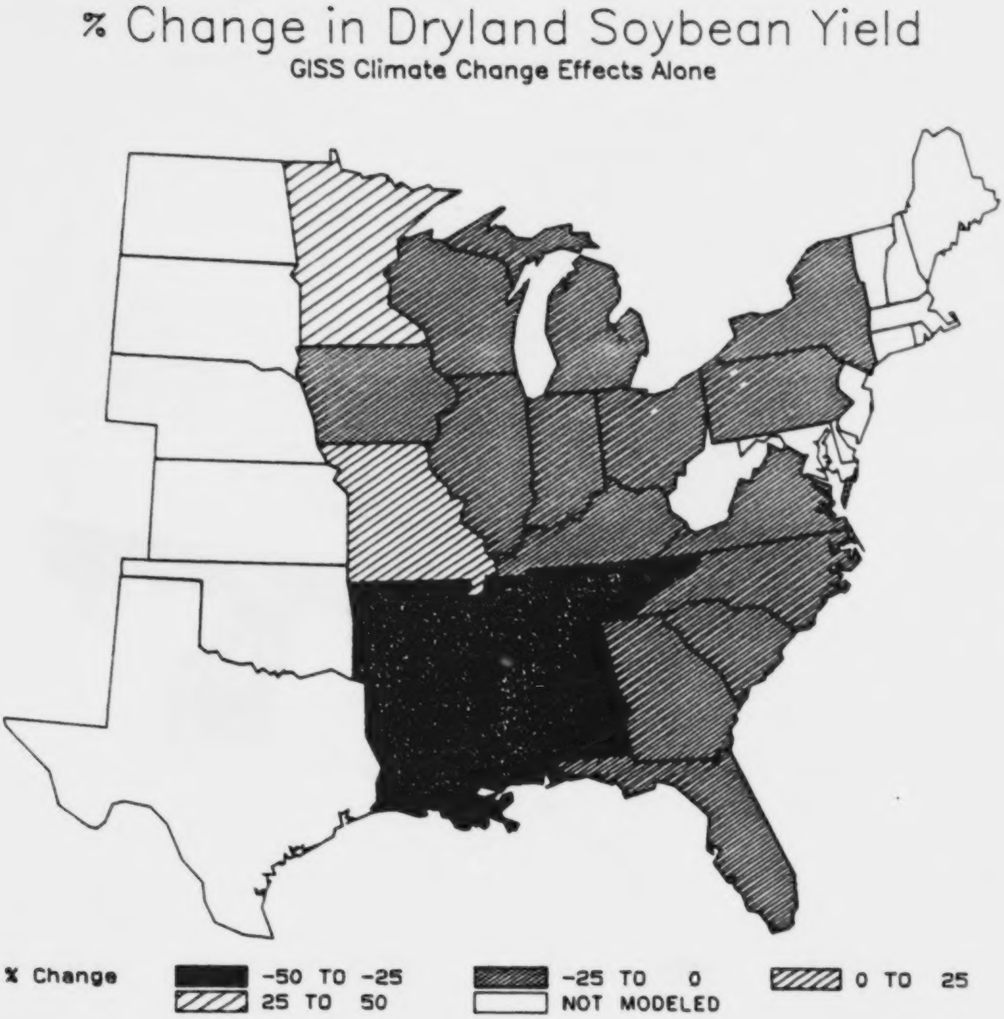
% Change in Dryland Soybean Yield
GISS Climate Change Effects Alone
% Change
-50 TO -25
25 TO 50
-25 TO 0
NOT MODELED
0 TO 25

Figure 10-3. Percent change in rainfed soybean yields simulated by the SOYGRO model with the GISS climate change scenario.

Source: Peart et al. and Ritchie et al., Volume ___.

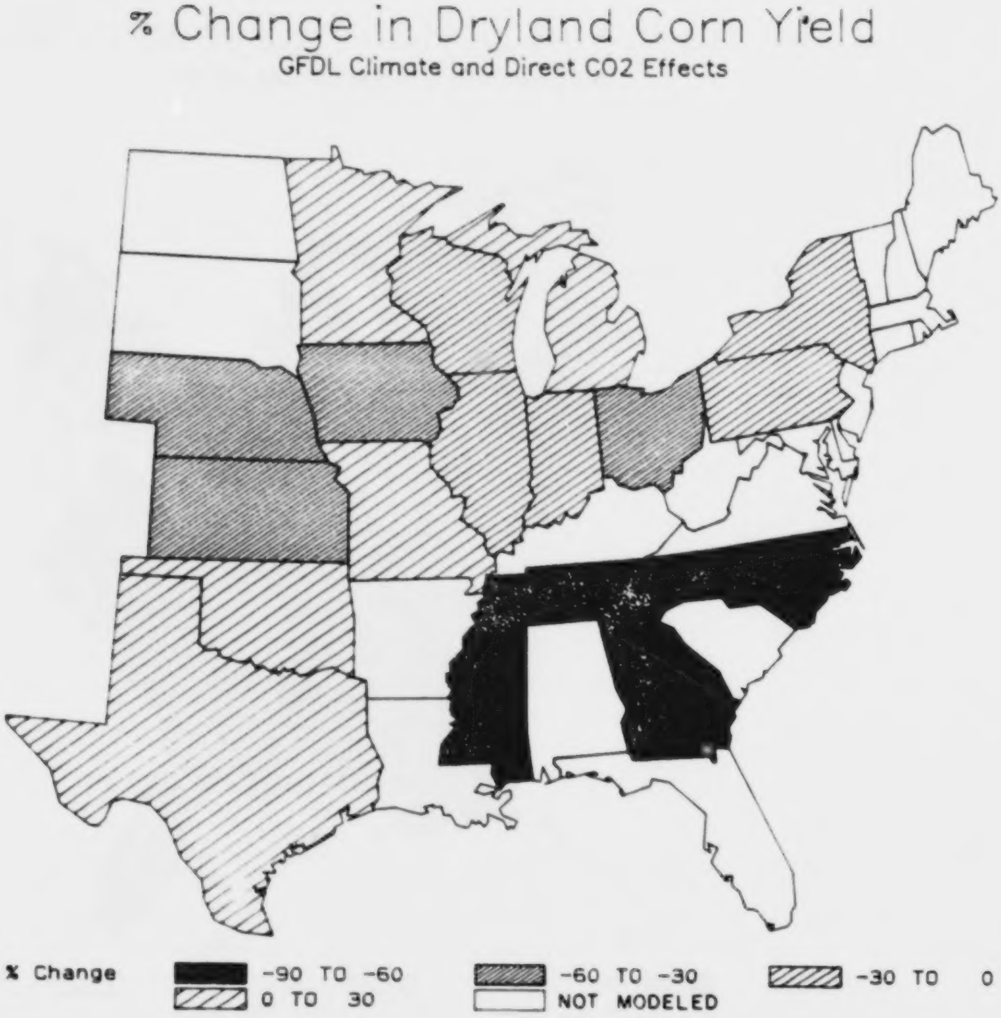
% Change in Dryland Corn Yield
GFDL Climate and Direct CO2 Effects
% Change
-90 TO -60
-60 TO -30
-30 TO 0
0 TO 30
NOT MODELED

Figure 10-4. Percent change in rainfed corn yields simulated by the CERES-Maize model for the GISS climate change scenario with approximated direct effects of CO_2 on photosynthesis and water use.

Source: Peart et al. and Ritchie et al., Volume ___.

The crop models were also used to test several possible adaptations by farmers to the predicted climate changes. For example, a corn variety that is better adapted to longer growing seasons was tested in Indiana. This later maturing variety did not compensate entirely for the yield decreases caused by the warmer climate change scenarios.

Implications

An implication of the crop modeling studies is that pressure for increased irrigation may grow in many agricultural regions. If the major agricultural areas are to continue to provide a stable supply of food under the predicted changes in climate, supplemental irrigation may be required for many soils. This could further tighten water supply problems in some areas and increase pollution from nonpoint sources (i.e., pollution that is not traceable to any one distinct source, such as agricultural pollution).

The water supply for the irrigation needed to stabilize production would come from both surface and subsurface sources, depending on the region. However, considerable uncertainty exists regarding the future availability of surface water and groundwater supplies with climate change, and concerning the costs of using or extracting the water. (See the Water Resources chapter of this report.)

Regional and National Economics Study

The estimated yield changes from the crop modeling studies and projected changes in irrigation water demand and availability were introduced into an agricultural economic model to translate the physical effects of climate change into economic consequences. Adams et al. (see Volume _) estimated the regional and national economic implications of changes in yields of wheat, corn, soybeans, and other crops and in the demand for and availability of water associated with alternative global climate change scenarios. In addition, sensitivity analyses on critical assumptions were also performed -- particularly for technological change and yield benefits due to the direct effects of increased CO_2.

Study Design

A spatial equilibrium agricultural model developed by Adams et al. (1984) was used to represent production and consumption of numerous agricultural commodities for the U.S. farm production regions as designated by the USDA (see Figure 10-5). The model has been used to estimate agricultural losses due to increased

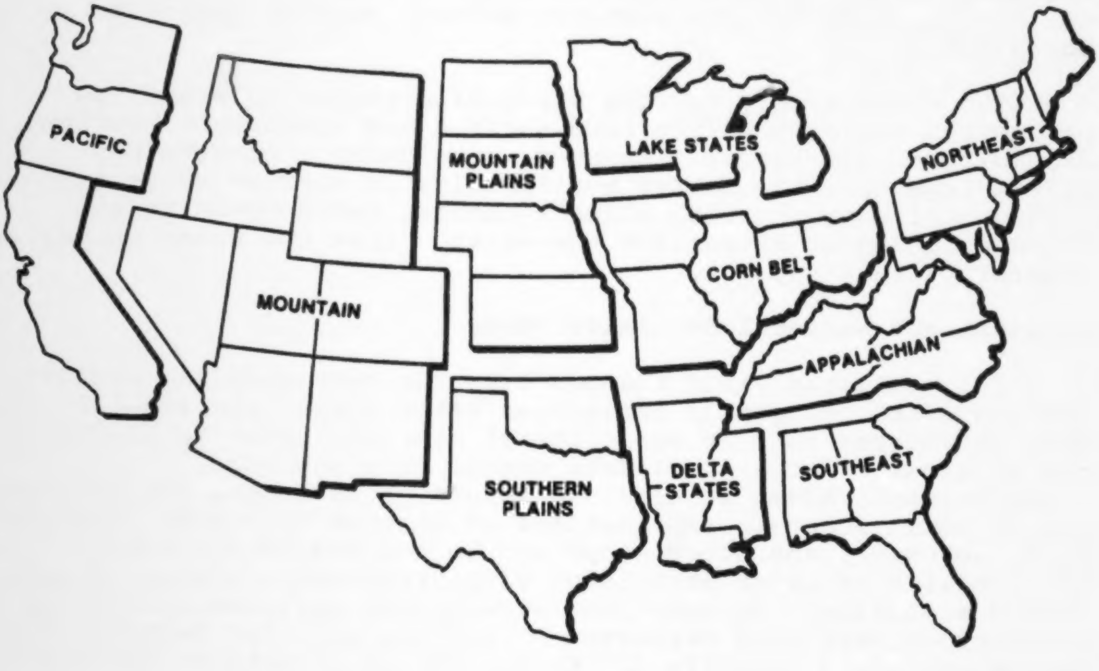
PACIFIC
MOUNTAIN
MOUNTAIN PLAINS
LAKE STATES
NORTHEAST
CORN BELT
APPALACHIAN
SOUTHERN PLAINS
DELTA STATES
SOUTHEAST

Figure 10-5. Farm production regions in the United States.

Source: USDA Economic Research Service (1987).

ultraviolet-B (UV-B) radiation caused by stratospheric ozone depletion (Adams et al., 1984). It consists of farm-level models for production regions, integrated with a national-level model of the agricultural sector. Both irrigated and nonirrigated crop production and water supply relationships are included for most regions. The model stimulates a long-run, perfectly competitive equilibrium, and was developed using 1980-83 economic and environmental parameters.

Limitations

The economic approach used in this study has several limitations. The economic model is static in the sense that it simulates an equilibrium response to climate change, rather than a path of future changes. Substitution of appropriate crop varieties and adjustments in farm management techniques were not included, thus possibly overestimating the negative effects of climate change. Estimates of the beneficial direct effects of CO_2 on crop yields may have biased results in the positive direction. Furthermore, changes in yields used as inputs to the economic model were only modeled for wheat, corn, and soybeans for a limited number of sites and regions, and national estimates were derived from these for all other crop commodities in the model. This introduces uncertainties into the results.

Potential changes in international agricultural supply, demand, and prices due to climate change are not explicitly included in the model. Such changes could have major impacts on U.S. agriculture.

Results

The economic model showed a small to moderate aggregate loss in economic welfare associated with the projected crop yield and hydrologic changes derived from the climate change scenarios (see Table 10-3). For the moderate climate change scenario, net losses were small; for the more extreme scenario, they were greater.

Production of most crops was reduced because of yield declines and limited availability of land and resources. The largest reductions were in sorghum (-20%), corn (-13%), and rice (-11%), because these estimated losses are equivalent to 5 and 28% of the 1982 value of crop and livestock commodities produced in the United States. The magnitudes of these changes, which are annual, may be compared to the estimated $6 billion cost of the Drought Relief Bill for 1988. In general, consumers lose and producers gain due to the increased prices of agricultural

Table 10-3. Aggregate Economic Effects of GISS and GFDL 2xCO_2 Global Climate Change on U.S. Agriculture (in billions of 1982 dollars)

Run	Economic Effects		
	Consumers	Producers	Total
GISS Analysis 4[a]	-7.3	+1.5	-5.0
GFDL Analysis 4	-37.5	+3.9	-33.6

[a] Analysis 4 includes the crop yield and irrigation water supply and demand consequences of climate change throughout the United States.

Source: Adams et al., Volume _.

commodities and inelastic demand (insensitivity to price changes) for agricultural crops.

Agricultural activity would shift northward with both GISS and GFDL climate change scenarios (see Figure 10-6). Land under production in Appalachia, the Southeast, the Mississippi Delta, and the Southern Plains, could decrease by 5 to 25%, while in the Lake States, the Northern Plains, and the Pacific it could increase by 5 to 17%. Irrigated acreage is estimated to increase in all areas, primarily because irrigation becomes economically feasible as agricultural prices rise (see Figure 10-7). Demand for additional water may be met in part by increased groundwater pumping, although this could be a matter of concern in areas where groundwater is already being overdrawn. Since changes in precipitation and recharge patterns are likely with climate change, the availability of groundwater and the costs to extract it might also be affected (see chapter on Water Resources).

The impact of higher CO_2 levels on crop productivity would probably reduce the negative economic impacts of climate change on the agricultural sector (Table 10-4). Under the less severe GISS climate scenario, the CO_2 direct effects would sufficiently counter the climatic effects in most regions, so that the net effect would be a gain in economic welfare. Consumers would be the primary beneficiaries, though (in aggregate) producers would also gain slightly. However, because the climatic effects on crops differ by region, the output of some regions would increase, while that of others would decrease. With the more severe GFDL climate change scenario combined with the direct effects of CO_2, economic welfare still would decrease, but not by as much as it did with the climate change scenarios alone. Here, consumers would be the losers.

Technological change, such as higher yielding crop varieties, chemicals, fertilizers, and mechanical power, has historically enabled agriculture to increase production with the same amount of or less land, labor, and other resources. When the effect of future technological change was modeled along with the less severe GISS climate change effects (without the direct effects of CO_2), most of the adverse climate effects were offset. Under the severe GFDL climate change scenario, continued and substantial improvements in yields would be required to overcome the climate change effects. Stated another way, the adverse effects of climate change would negate most of the higher output attributable to improved technology over the next 50 years.

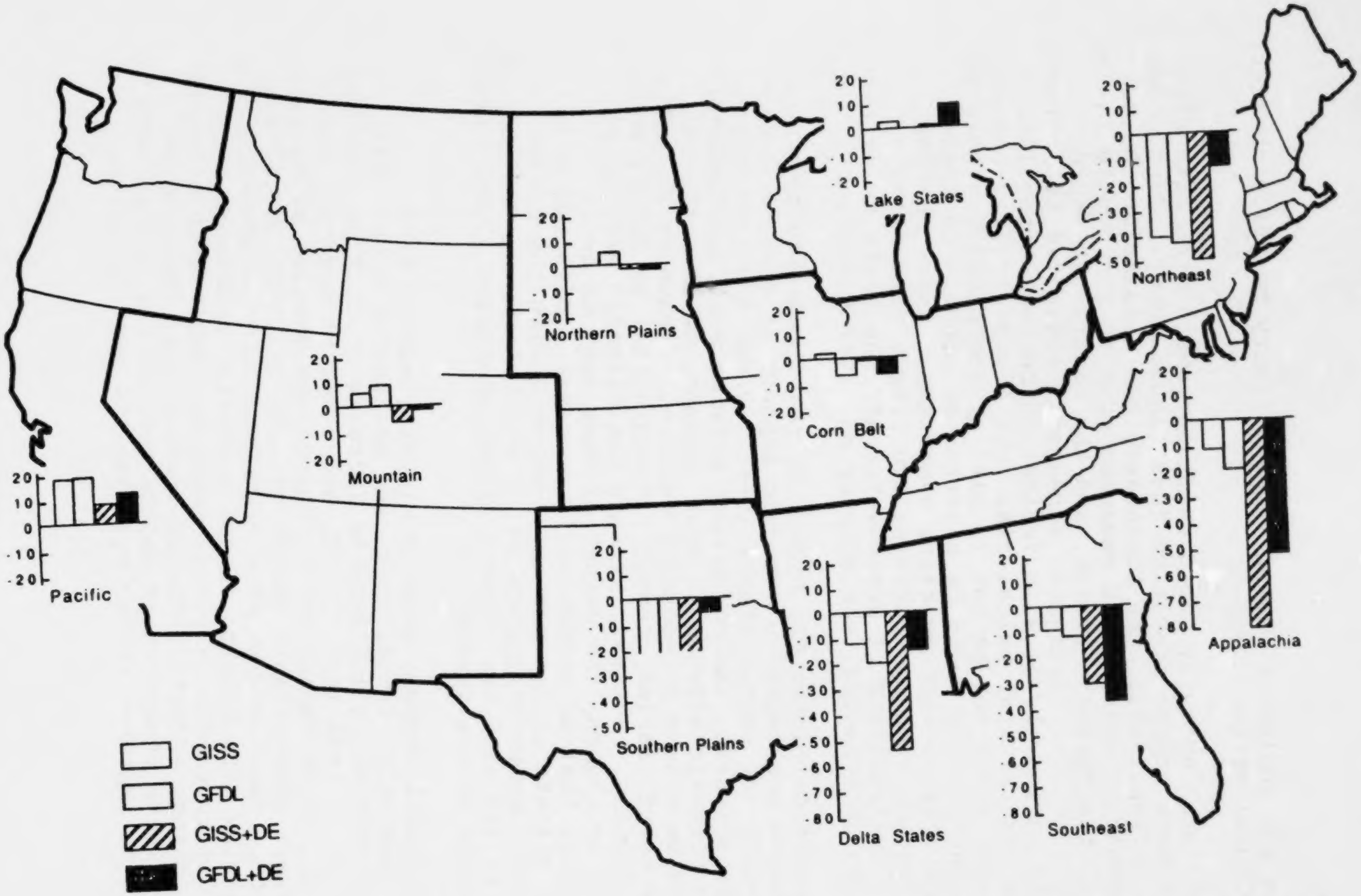
Pacific
Mountain
Northern Plains
Southern Plains
Lake States
Corn Belt
Delta States
Southeast
Appalachia
Northeast
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
GISS
GFDL
GISS+DE
GFDL+DE

Figure 10-6. Percent change in regional agricultural acreage simulated by an economic model of the U.S. agricultural sector for the GISS and GFDL climate change scenarios with and without the direct effects of CO_2 on crop yields.

Source: Adams et al., Volume _.

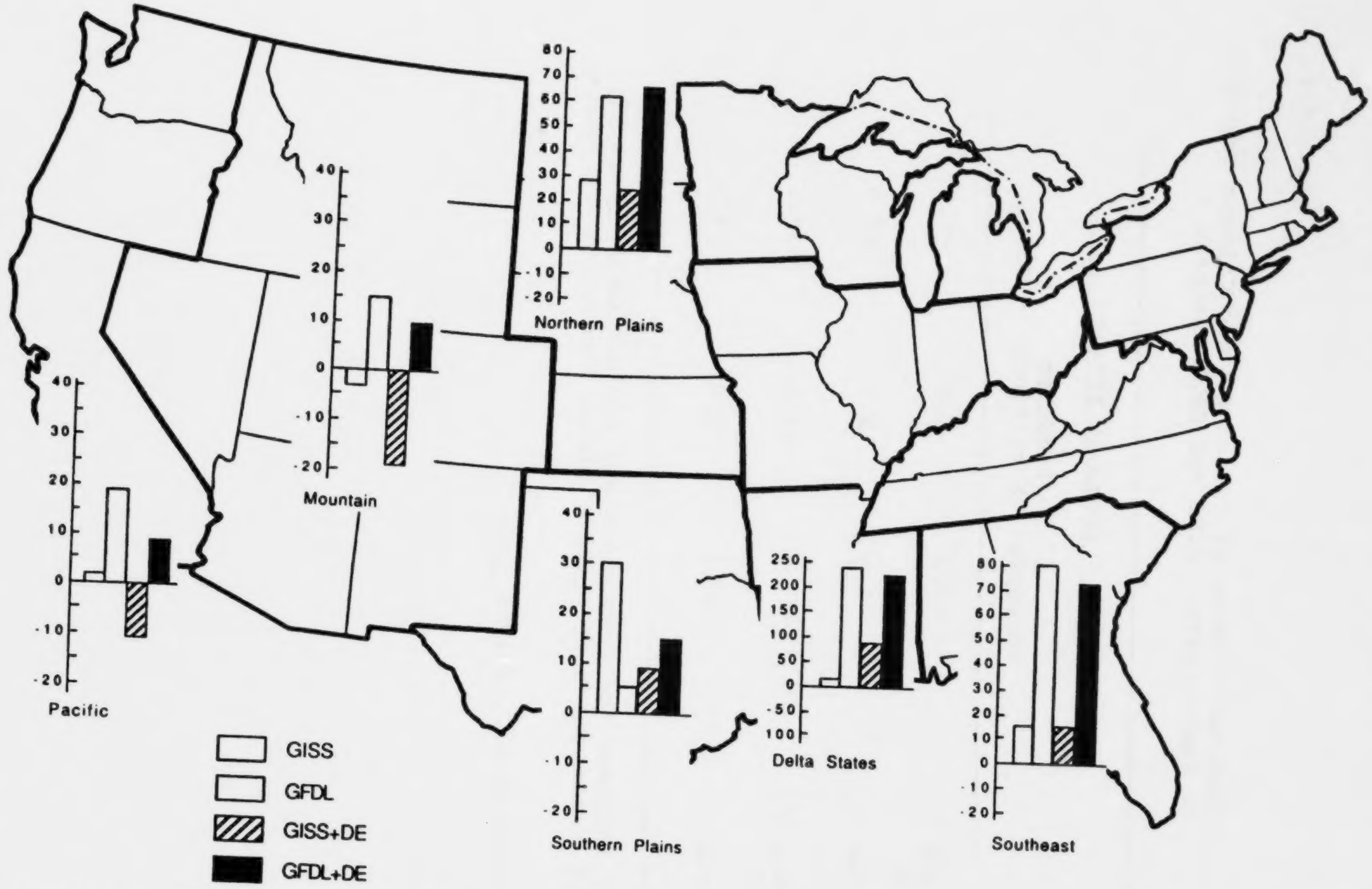

Figure 10-7. Change in regional irrigation acreage simulated by an economic model of the U.S. agricultural sector for the GISS and GFDL climate change scenarios with and without the direct effects of CO_2 on crop yields.

Source: Adams et al., Volume _.

Table 10-4. Combined Effects of Direct CO_2 and Climate Change on Agriculture: GISS and GFDL Analyses 4

Run	Economic Effects Consumer	 Producer ($ billion)	 Total
GISS Analysis 4: without CO_2	-7.3	1.5	-5.9
GISS Analysis 4: with CO_2	9.4	1.3	10.6
GFDL Analysis 4[a]: without CO_2	-37.5	+3.9	-33.6
GFDL Analysis 4: with CO_2	-10.3	0.6	-9.7

[a] Analysis 4 includes the crop yield and irrigation water supply and demand consequences of climate change throughout the United States.

Source: Adams et al., Volume _.

Implications

Food Supply

Although climate change could reduce the productive capacity of U.S. agriculture, the reduction does not imply major disruption in the supply of basic commodities for American consumers. Domestically, consumers would face slightly to moderately higher prices under some analyses, but supplies would be adequate to meet current and projected domestic demand. However, most exported commodities in some scenarios decline by up to 70%, assuming the demand for exports remains constant.

While climate change does not appear to be a food security issue within the United States, supply and demand for agricultural commodities could shift among international regions. Responses of U.S. agriculture would take place in this global context. These changes in global agriculture cannot be determined without analyzing the potential impacts of climate change on both major world agricultural production regions and potentially vulnerable food deficit regions.

Regional Economics and Land Use

Regional shifts in U.S. agricultural production patterns are highly likely, as all analyses showed a consistent northward shift in the production of the major commodities of wheat, corn, and soybeans (see Figure 10-6). Other crops, including specialty crops such as vegetables and fruits, could also shift. Where agricultural acreage declines, this might further weaken an economic base already under pressure from long-term structural changes in U.S. agriculture.

Environmental Concerns

Regional agricultural adjustments could place environmental resources at risk. Where agricultural acreage would increase, demands for natural resources, such as soil and water, might intensify current pressures on environmental elements, such as rivers, lakes, aquifers, wetlands, and wildlife habitats. Northern States, such as Minnesota and North Dakota, could become more productive for annual crops like corn and soybeans because of warmer temperatures and a longer frost-free growing season. Because of the presence of forests and wetlands in these regions, increased agricultural production in the area might threaten natural ecosystems, including wildlife habitats such as prairie potholes for ducks and flyways for bird migrations.

In addition, many of the glacial till soils in the northern latitudes are not as productive as Corn Belt soils. Thus, large increases in production of crops would most likely require increased applications of chemical fertilizers. The use of these fertilizers in humid regions on glacial till and sandy soils is now creating an environmental hazard to the underlying groundwater, receiving waters, and aquatic habitats in many areas. With climate change, water and fertilizer use would have to be carefully managed to minimize still more leaching of water-soluble nutrients such as nitrogen and potash, while continuing to provide enough nutrients for crop growth.

Demand for Water for Irrigation

Water is the single most critical factor in determining the development, survival, and productivity of crops. The amount of water that crops use and thus the demand for irritation water are governed largely by the evaporation process. The projected higher air temperatures due to increasing trace gases in the atmosphere could heighten evaporative demands. Farmers may irrigate more to satisfy these higher demands, which could accelerate depletion of groundwater and surface water resources. Also, the rate of evaporation might outstrip precipitation, thus decreasing crop yields.

Studies reported in the California and the Great Plains case studies (see Chapters 4 and 5) explicitly examined the potential changes in demand for water for irrigation. In these regions, water is a critical resource for agriculture; California and the parts of the Great Plains fed by the Ogallala Aquifer, in particular, depend very heavily on irrigation for crop production.

Irrigation Requirements in the Great Plains

Allen and Gichuki (see Volume _) computed irrigation water requirements for sites in the Great Plains for the baseline climate and the GISS and GFDL climate change scenarios. The direct effects of CO_2 and water use were also included. (See Chapter 7, Great Plains, for study design and limitations.) Major changes in irrigation water requirements were observed at all locations in the Great Plains, for all crops (see Figure 10-8). The most significant were the persistent increases in seasonal net irrigation water requirements for alfalfa, which were driven by the climate changes in temperature, wind, humidity, and solar radiation, and by the lengthening of the growing season. Decreases in irrigation requirements were observed for winter wheat and corn in most regions. These decreases were attributed to earlier planting dates and the shortening of the crop-growing

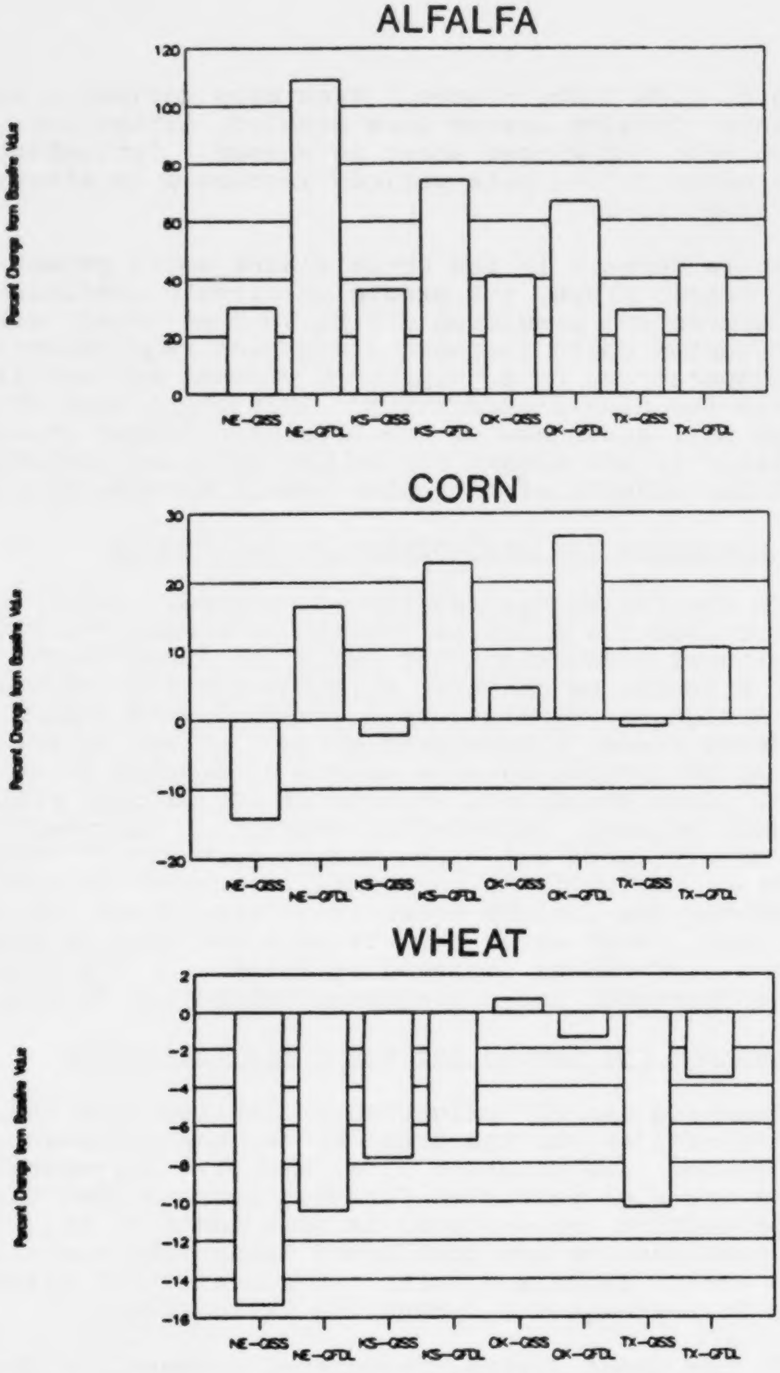

Figure 10-8. Percent change in net seasonal irrigation requirements with a 20% increase in bulk stomatal diffusion resistance.

Source: Allen and Gichuki, Volume __.

season by high temperatures. When crop varieties appropriate to the longer growing season were modeled, irrigation water requirements for winter wheat increased. Irrigation water requirements during peak periods increased in almost all areas (see Figure 10-9).

While farmers in the Great Plains would probably shift to longer season crops, the predicted climate conditions (warmer temperatures and predicted drying in some areas) during the later summer months could increase irrigation requirements and elevate leaf temperatures to a point that exceeds optimum temperatures required for high productivity. This might make it uneconomical to take full advantage of the predicted longer growing season, especially if the higher CO_2 levels increase photosynthesis and offset the effects of a shorter season to some degree.

Water Resources for Agriculture in California

In the California regional case study, Dudek (see Volume _) characterized the potential shifts in demand for water for agricultural production that would accompany shifts in cropping patterns driven by changing climate. (See California chapter for study design and limitations.) When climate change was considered alone, groundwater extraction and surface water use declined in California as a result of changes in both supply and demand. When the direct effects of CO_2 on crop yields were included, however, groundwater extraction increased due to improved yields of all crops except corn and to enhanced economic welfare. Institutional responses to changes in surface and groundwater use include water transfers, which improve irrigation efficiency. When water markets were included in the simulations, economic welfare was improved by 6-15% over the base, while crop acreage increased and groundwater extraction decreased.

Implications for Demand for Water for Irrigation

Expanded use of irrigation is implied from the regional crop modeling studies for the Great Lakes, the Southeast, and the Great Plains (see Chapters 5, 6, and 7). Increases in irrigated acreage are also predicted for most regions when the economics of crop production are factored in (see Adams et al., Volume _). When these results are considered along with the other Great Plains and California studies, it appears that climate change is likely to increase the demand for irrigation.

In the Great Plains, heightened evaporative demand and variability of rainfall may increase the need for irrigation in dryland farming regions. The projected changes in irrigation water requirements are varied, and specific crops and locations

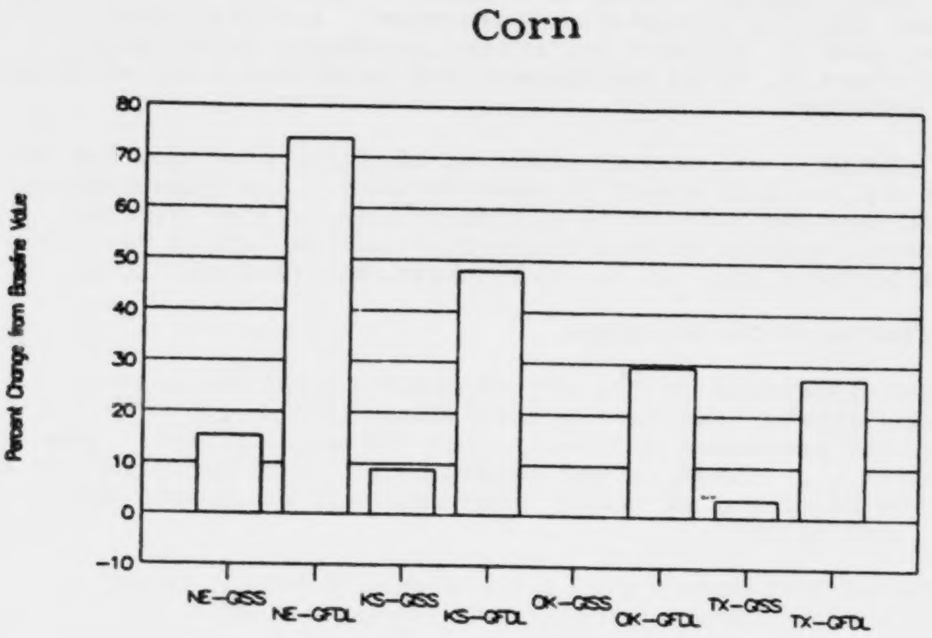

Figure 10-9. Percent change in peak irrigation requirements of corn with a 20% increase in bulk stomatal diffusion resistance.

Source: Allen and Gichuki, Volume _.

probably will be affected differently. Higher peak irrigation water requirements for some crops may require larger capacity irrigation systems and enlarge energy demands.

Intensified extraction of water poses serious environmental and economic problems, especially in areas where groundwater is being overdrawn. Streamflows also may slacken if more surface water is used for irrigation, thereby aggravating water quality problems. This in turn would harm fish, wildlife, and recreational activities.

Regional changes in cropping locations and patterns of water use also could exacerbate agricultural, nonpoint source pollution and further deplete groundwater resources. Institutional responses, such as markets for water transfers, could help improve irrigation water management and alleviate some of these negative effects.

The economic and social costs of shifting the location of irrigated agriculture could be considerable. The construction of irrigation systems consisting of reservoirs, wells, ditches, pipes, pumps, and sprinklers currently requires about $1,500-5,000 per hectare (ha) in capital investment (Postel, 1986).

Direct Effects of CO_2 on Crops

Global increases in CO_2 are expected to influence crop metabolism, growth, and development directly through physiological processes and indirectly through climate. Rose (see Volume _) reviewed recent experimental work performed on the direct effects of CO_2 on crops, with emphasis on wheat, corn, soybeans, and cotton.

Elevated concentrations of CO_2 directly affect plant processes such as photosynthesis and transpiration. CO_2 concentrations are also expected to influence these processes indirectly through predicted increases in temperature and other changes in climate variables such as precipitation. Because experimental research has rarely simultaneously studied both the direct and indirect effects of plant responses, it is difficult to assess the relative contributions of elevated CO_2 and climate changes to predictions of crop responses.

Research on the physiological effects has focused primarily on responses of rates of photosynthesis and transpiration to increasing concentrations of atmospheric CO_2. Photosynthesis rates have increased in these crops in relatively ideal experimental environments. At moderate temperatures, most crops will probably show increases in size and possibly yield as CO_2

concentrations rise. However, plants also have internal regulation mechanisms that may lessen these effects under field conditions.

Transpiration rates per unit leaf area decrease, while total transpiration from the entire plant sometimes increases because of greater leaf area. Drought-stressed plants exposed to high partial pressures of CO_2 should be better able to cope with water deficits. Leaf temperatures in all species are expected to rise even more than air temperatures, which may inhibit plant processes that are sensitive to high temperature.

Few studies have examined the interactive effects of CO_2, water, nutrients, light, temperature, pollutants, and sensitivity to daylength on photosynthesis and transpiration. Even fewer studies have examined the effects of these interactions on the growth and development of the whole plant. Therefore, considerable uncertainty exists concerning the extent to which the beneficial effects of increasing CO_2 will be seen in crops growing in the field under normal farming conditions with climate change.

Climate Impacts on Pest-Plant Interactions

Compared to the existing information on the potential effects of climate change on crop production, relatively little effort has been directed toward assessing the influence of climate change on plant-pest interactions. Atmospheric increases in temperature and CO_2, and changes in moisture regimes, all can directly or indirectly affect interactions between pests and crops.

Study Design and Results

Stinner et al. (see Volume _) conducted a literature survey and modeling experiments on the major mechanisms through which climate change may affect pest-plant interactions. This study emphasized the major insect pest and pathogen species of corn and soybeans. The survey indicated that temperature and precipitation patterns are the key variables that affect crop-pest interactions. The temperature increases associated with the climate change scenarios bring about the following trends: (1) increased survival for migratory and nonmigratory insect pest species in the winter, (2) northern range extensions of current pests in the higher latitudes and migration of southern species into the northern Grain Belt regions, (3) an increase in pest species with more than one generation per year in the northern

Grain Belt, (4) earlier establishment of pest populations in the growing season, and (5) increased abundance of pests during more susceptible growth stages of crops.

The potential changes in the overwintering ranges of four major pests were mapped for the GISS and GFDL climate change scenarios and were compared to present ranges. The overwintering capability of the four major pests may extend northward with both climate change scenarios. For example, the potato leafhopper, a serious pest on soybeans and other crops, at present overwinters only in a narrow band along the coast of the Gulf of Mexico (Figure 10-10). Warmer winter temperatures predicted by both the GFDL and GISS models suggest a doubling or tripling of the overwintering range in the United States, respectively. Increases in the winter population density of this size would increase the invasion populations in the northern States by similar factors. The invasions also would be earlier in the growing season, assuming planting dates do not change. Both features are likely to lead to greater insect density and damage. This pattern is repeated with the other three pests studied and indicates that these pests, and possibly others, may move northward and invade cropping systems earlier in the growing season under climate change conditions.

The Soybean Integrated Crop Management (SICM) model (Jones et al., 1986) was run with the GISS and GFDL climate change scenarios to estimate changes in damages caused by corn earworm. Modeling results show that earworm damage to soybeans will increase in severity in the Grain Belt under a warmer climate. Such damage could cause grain farmers in the Midwest to suffer significant economic losses. These results were particularly marked with the warmer and dryer GFDL scenario.

Study Limitations

Lack of knowledge about the physiological effects of CO_2 on crop plants and lack of experimental evidence on direct effects of CO_2 on insect-plant interactions make the study of pest-plant interactions particularly difficult. Only one cultivar is used in the modeling study under both the baseline and the climate change scenarios. In reality, farmers would probably switch to a more climatically adapted cultivar as climate changed.

Study Implications

Increased pest-related crop damage could intensify pesticide use. The economic and environmental ramifications of such an increase could be substantial, not only in current farming regions but also in new areas as agriculture shifts to the more

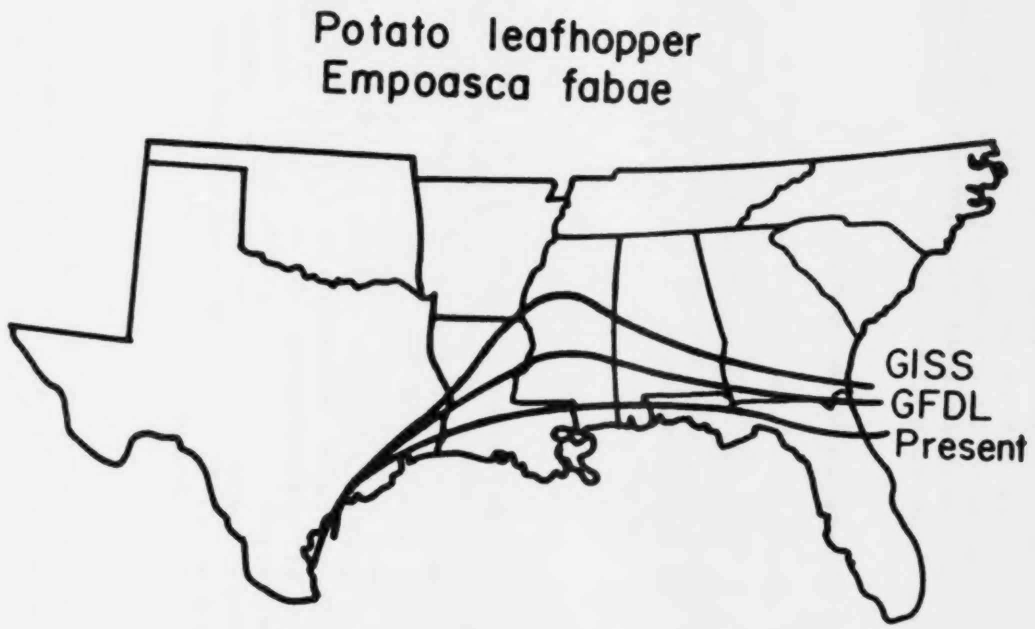
Potato leafhopper
Empoasca fabae
GISS
GFDL
Present

Figure 10-10. Present and potential (GISS and GFDL climate change scenarios) overwintering range of the potato leafhopper, Empoasca fabae, a major pest of soybeans.

Source: Stinner et al., Volume __.

northern regions such as the Northern Plains, the Great Lakes States, and the Pacific Northwest (see Figure 10-6).

Increased use of pesticides would create additional threats to the integrity of ecosystems through soil and water contamination and could increase risks to public health. If agricultural production is not to rely increasingly on chemicals that are potentially harmful to the environment, an increased need will exist for alternative pest management strategies such as biological control, genetic resistance, and innovative cropping systems.

Effects of Climate Change on Water Quality

Agricultural pesticides are ranked as a high priority pollution problem in many rural regions. Potentially toxic agricultural chemicals can be transported away from fields via runoff of surface soils and via downward leaching and percolation through the soil. An understanding of these processes is essential to the evaluation of potential threats to drinking water quality caused by climate change.

Study Design

Johnson et al. (see Volume _) modeled the partitioning of agricultural pesticides among uptake, degradation, surface runoff, and soil leaching for wheat, corn, and cotton production regions in the Great Plains and the Corn Belt. (See the Great Plains chapter of this report for details of the study.) They used the Pesticide Root Zone Model (PRZM) (Carsel et al., 1984), which simulates the vertical movement of pesticides in the soil. The model consists of hydrological and chemical transport components that simulate runoff, erosion, plant uptake, leaching, decay, foliar washoff, and volatilization of a pesticide. The interactions among soil, tillage, management systems, pesticide transport, and climate change were studied.

Limitations

The frequency and duration of precipitation remain the same in the climate change scenarios, even though these storm characteristics are critical factors in determining the transport of agricultural chemicals and may change. The scenarios assume that the number of days with rainfall does not change, but the intensity of rainfall increases or decreases. Runoff and leaching estimates would most likely be different if the number of days of rainfall changed and daily rainfall amounts were held constant.

The PRZM is a one-dimensional, point model that does not simulate the transport of water below the root zone. Thus, results on a regional basis must be extrapolated with care. The direct effects of CO_2 on crop growth, which may increase the size of the plants and the extent to which crops cover the soil, are not included.

Results

Regional changes in chemical loadings of water and sediment are likely but probably will not be uniform. There appears to be some consensus between the GCM scenarios concerning the estimated regional changes (Table 10-5). Modeled pesticides in runoff increase in the cotton production area, and pesticides carried by sediments decrease in the spring wheat and corn regions. Leaching of pesticides tends to be less everywhere owing to changes in seasonal precipitation and increased evaporation.

Implications

When the changes in water quality from the predicted climate change scenarios are considered in conjunction with the predicted increases in pests and implied higher applications of pesticides described in the study on pest-plant interactions, the potential for changes in the nation's water quality becomes apparent. Any deterioration in water quality could adversely affect public drinking water supplies and human health.

Climate Variability

The impacts of climate change result not only from a slow change in the mean of a climate variable but often from shifts in the frequency of extreme events. Droughts, freezes, and prolonged periods of hot weather have strong effects on agricultural production. While the agricultural modeling studies did not include the effects of potential changes in climate variability, Mearns and Schneider (see chapter on Climate Variability in this report) reviewed literature on agriculture and extreme events to determine the nature and magnitudes of significant impacts.

Corn, soybeans, wheat, and sorghum are sensitive to high maximum temperatures during blooming. Lower yields of corn, wheat, and soybeans have been found to be correlated with high temperatures. The damaging effect of runs of hot days on corn yields was particularly evident in 1983 in the U.S. Corn Belt.

Although low temperatures may be less of a problem with the predicted climate change, risks of frost damage to crops may

Table 10-5. Summary of GCM Model Consensus of PRZM Pesticide Transport by Cropping Region and Pesticide[a]

	Surface Pesticides Runoff Losses	Surface Pesticide Erosion Losses	Pesticide Leaching
SPRING WHEAT:			
Highly soluble/short-lived[b]	+	+	-
Highly soluble/long-lived		+	-
Slightly soluble/long-lived			-
WINTER WHEAT:			
Highly soluble/short-lived		+	+
Highly soluble/long-lived	+		-
Slightly soluble/long-lived			-
COTTON:			
Highly soluble/short-lived	+		+
Highly soluble/long-lived	+	+	-
Slightly soluble/long-lived	+	+	-
CORN:			
Highly soluble/short-lived	-	-	
Highly soluble/long-lived		-	-
Slightly soluble/long-lived	-	-	-

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[a] + indicates that median values increase under climate change; - indicates that median values decrease under climate change; blank indicates no consensus among median values.

[b] ex. median value of all tillage, soil, weather site scenarios for highly soluble/short-lived pesticides in the spring wheat crop area.

Source: Johnson et al., Volume _.

change in the growing areas of certain crops. Citrus trees are very vulnerable to low minimum temperatures. Winter wheat is often damaged by low temperatures known as winter kill, especially in the absence of snow. (See Glantz, Volume _, for a discussion of how the Florida citrus industry adapted to increased frequency of freezes in the 1980s.) Even with warmer winters and fewer frosts, more damage can occur at less extreme temperatures. For example, the effect of freezing temperatures is exacerbated if the crops have not yet been hardened by the cold, or if they are no longer dormant and a cold snap occurs.

Drought is a major cause of yearly variability in crop production. In the Dust Bowl years of the 1930s, yields of wheat and corn in the Great Plains dropped to as much as 50% below normal. In 1988, agricultural disaster in areas of the northern Great Plains demonstrated a high vulnerability to drought; and nationwide a nearly 40% decrease in U.S. corn yields is predicted. Reduction in vegetative cover associated with drought also brings about severe wind erosion of soils, which will affect future crop productivity. Low yields of forage crops during droughts result in food shortages for livestock and premature selling of livestock.

Farm-Level Management and Adjustments to Climate Change

Adjustments to existing production practices are the first course of action in the face of climate change. The net effect of climate change with adjustment by farmers may be significantly different from the estimated effects of climate change alone.

Study Design

Several studies addressed possible adjustments that could modify the effects of climate change. These adjustments include changes in planting and harvesting dates, tillage practices, crop varieties, application of agricultural chemicals, irrigation technology, and institutional responses for management of water resources.

Results of Adjustment Studies

Ritchie et al. demonstrated that the yield reduction in corn in the Great Lakes can be partly overcome with selection of new cultivars that have a longer growing season (see Great Lakes chapter of this report). Rosenzweig (see Great Plains chapter of this report) showed that adjusting the planting date of winter wheat to later in the fall did not ameliorate the effects of climate change, but that changing to varieties more suited to the predicted climate overcame yield decreases at some locations.

Dudek's California study found that flexible institutional responses to climate change helped to compensate partly for negative climate change effects (see California chapter of this report). By allowing movement of water around the State by transferring water rights, California water resource managers can alleviate some groundwater extraction and compensate for surface water reductions.

Easterling (see Great Lakes chapter of this report) found that potential farmer adjustments to climate change include changes in tillage practices, increased fertilizer application, more full-season and heat-resistant varieties, changes in planting densities, higher pesticide use, earlier harvest, and less artificial drying. Different adjustments would occur at different times in the cropping season. With the hotter and drier GFDL scenario, farmers may be forced to adopt production practices that are different from those in use today. Climate changes that leave soils drier during summer than they are at present will most likely lead to increased use of irrigation in the Corn Belt. This increased use of irrigation is also supported by the projected price increases for all crops grown in Illinois.

Implications of Adjustment Studies

Although detrimental climate change effects on agriculture may be partly offset naturally by increased photosynthesis and water-use efficiency caused by higher levels of atmospheric carbon dioxide, farmers will no doubt use a variety of adjustments to adapt to climate change. Market forces also will aid adaptation to climate change because they help to allocate resources efficiently.

More severe climate changes are likely to necessitate major adaptations, such as farm abandonment in some regions. Prior investments may be lost as existing infrastructures become obsolete and new investments are needed for new locations. Some of these adjustments could be costly.

Improvements in agricultural technology also may be expected to ease adjustment by development of appropriate farming practices and crop variety and livestock species. Adjustment and adaptation to climate change should be included in agricultural research programs to enable this process to occur.

Livestock

Animal products are a critical source of protein, energy, vitamins, and minerals. U.S. livestock production, mainly from cattle, swine, sheep, and poultry, was estimated to be worth over $31 billion in 1986 (USDA, 1987).

Climate is known to significantly affect many aspects of animal health and production. The direct effects of climate change on animal health include differences in incidence of heat and cold stress, changes in weight gain, and decline in reproductive capabilities. Indirect effects may involve trends in agricultural commodities, such as the availability and prices of types of animal feeds and the expanded geographic distribution and activity of disease-carrying vectors.

Higher winter temperatures may lower the incidence of respiratory diseases in livestock (Webster, 1981). Conversely, warmer summers may necessitate more hours of indoor cooling during which pathogens are confined to housing structures. Climate warming may significantly increase the costs of air-conditioning in poultry housing. Changes in reproductive capabilities such as decreased ovulation rates, shortened intensity and duration of estrus, decreased fertility of males, and increased embryonic mortality also have been shown to occur with high temperatures (Ames, 1981).

Climate change may also affect the survivability, activity, and geographic distribution of vectors responsible for the transmission of infectious diseases in livestock. The activity and reproduction of disease-carrying vectors infecting livestock, humans, and crops are driven primarily by temperature, humidity, and precipitation. These impacts are likely to be similar to those on mortality and morbidity of disease in humans (see chapter on Human Health, this volume), and they also are similar to changes predicted for crop pests.

Design of Livestock Studies

Stem et al. (see Volume _) studied the available literature on four diseases to evaluate the range of potential changes in disease distribution and occurrence under climate change conditions. Schmidtmann and Miller (see Volume _) used a population dynamics simulation model to estimate the effects of the GFDL climate change scenario on the life cycles of the horn fly, a ubiquitous pest of pastured cattle throughout the United States.

Results of Livestock Studies

Stem et al. found that, under warmer conditions, livestock diseases currently causing serious economic losses in tropical countries could spread into the United States. Rift Valley fever is transmitted principally by mosquitoes, and danger of the disease may spread as rising winter temperatures become able to support an active increase in the mosquito population. African swine fever also may become more of a threat.

The ranges and activities of disease-carrying agents of blue tongue and anaplasmosis, diseases currently causing severe losses in cattle and sheep in the United States, may expand. If disease-carrying insects increase their winter survival and reproduce year-round in more States, the geographical distribution of blue tongue, which is caused by a virus, may expand northward and eastward. Anaplasmosis, a rickettsial infection of ruminants, is the second most important disease of cattle in the United States. The distribution of the habitat of the insect carrier of the disease could expand to northern States with climate change, and the day-to-day activity of the insects may increase, also causing an increase in disease transmission.

The horn fly causes annual losses of $730.3 million in the beef and dairy cattle industries (Drummond, 1987). Schmidtmann and Miller found that with the very warm GFDL climate change scenario, the horn fly season throughout most of the United States was extended by 8 to 10 weeks, horn fly populations increased (see Figure 10-11), and the average daily gain in beef cattle decreased. This horn fly increase will cause substantially greater reductions in the average daily gain of growing beef cattle. The GFDL simulation also increased pest activity in dairy cattle in the northern and northwestern States, a result that could significantly decrease milk production. Conversely, the summertime activity of the horn fly decreased in the southern States because the warmer climate exceeded the horn fly's tolerance to high temperatures.

Limitations

Horn fly data are based on counts taken at various times, under varying weather and management conditions. However, the prediction of current horn fly populations appears to be well correlated with observations. The model is not validated for the high temperatures predicted for the climate change. Schmidtmann and Miller used only the hottest scenario, GFDL; the other scenarios may have resulted in less of a geographic shift in the range of the horn fly.

It should be noted that this analysis is based on current livestock management breeds and distribution. Possible changes in these factors are beyond the scope of this study.

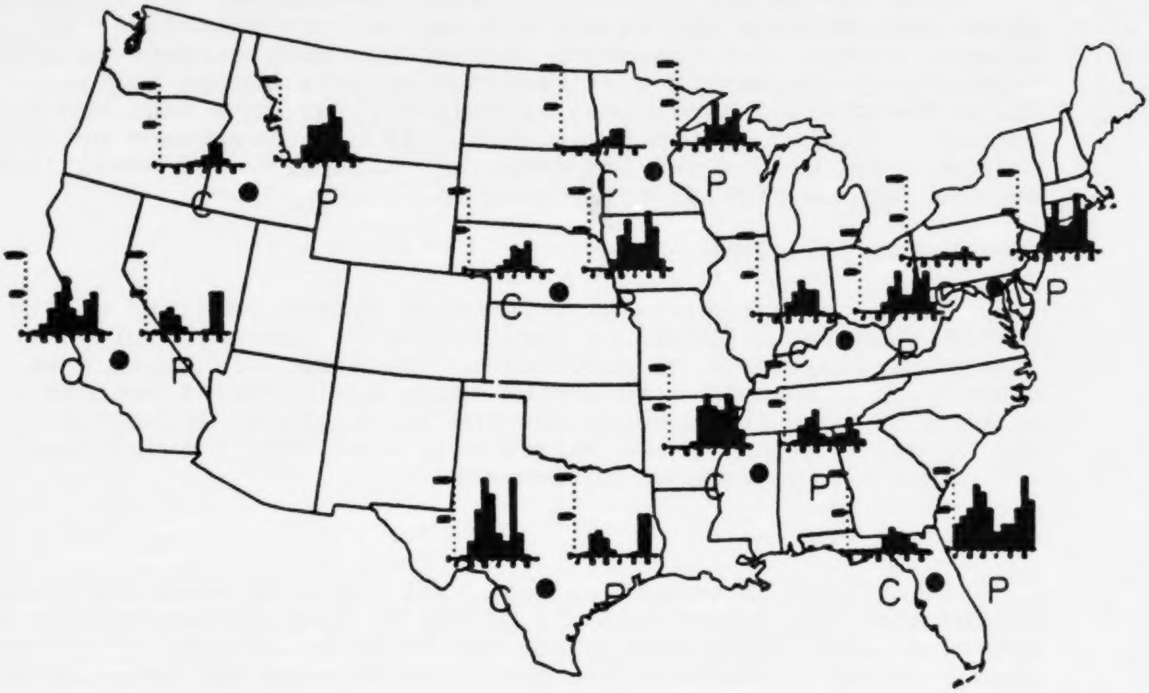
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Figure 10-11. Current (C) and projected (P) populations of the horn fly, a major pest of beef and dairy cattle, using the GFDL climate change scenario.

Source: Schmidtmann and Miller, Volume _.

Implications of Livestock Studies

With climate change, patterns of livestock diseases and pests may change. Tropical livestock diseases may become more of a threat, because more geographical areas are potential ranges for the insect carriers of the diseases. Temperature conditions may improve in the winter but may be exacerbated in the summer. Reproductive capabilities may be lower.

ECONOMIC AND ECOLOGICAL IMPLICATIONS

Even though the U.S. agricultural system has historically shown considerable resiliency and may be less vulnerable to climate change than unmanaged ecosystems, many reasons to avoid complacency concerning the predicted climate change remain. While the studies summarized in this chapter show that the U.S. supply of basic commodities probably is not threatened by climate change, food prices may increase for consumers, and agricultural exports may be significantly reduced.

Costs of Adjustments

Since our agricultural production system consists mostly of specialized farms producing commodities in geographically specialized patterns of production, the costs of adjustments to changes in comparative advantage among agricultural regions with ensuing changes in resource use and agricultural infrastructure may be quite high. These shifts will also entail involvement of and costs to the Federal Government.

Effects of CO_2

It is also important to note that the crop modeling studies showed that the direct effects of CO_2 on crop photosynthesis and water-use efficiency ameliorate the negative effects of climate change in some locations but not uniformly and not everywhere. While much work remains to be done to improve both climate and crop models, reliance on overly optimistic assessments about the beneficial effects of CO_2 must be avoided when policy options are considered.

Water Quality

Changes in the agricultural production system are likely to have significant impacts on resource use and the environment. Many of the agricultural studies suggest that climate warming could result in changes in water quality from agricultural chemicals, increases in pesticide usage to control changes in pest vectors, and accelerated rates of demand for water for irrigation. Climate change could thus exacerbate many of the current trends in environmental pollution and resource use associated with agriculture as well as initiate new ones.

A northward migration of agriculture will increase the use of irrigation and fertilizers on sandy soils, thus endangering underlying groundwater quality. From South Dakota to southern Canada, critical prairie wetlands may be lost to drainage and conversion to cropland. Many of these areas are important wildlife habitats. Shifts in agricultural activities may increase the susceptibility of soils to wind and water erosion.

Global Agriculture

Finally, U.S. agriculture is an integral part of the global, international agricultural system. Consequently, the adjustment of U.S. agriculture to climate change cannot be considered in isolation from the rest of the world. The optimal configuration of U.S. adjustments will depend very much on how simultaneous changes in regional climate affect global agriculture and how other countries, in turn, respond to those changes.

NATIONAL POLICY IMPLICATIONS

Since climate change appears likely to reconfigure the agricultural activities and demographics of rural America, policies are needed to ease the inevitable adjustments and ensure the sustainability of our natural and human resources (see Schuh and Dudek, Volume _). Following are specific policy areas that policymakers could investigate to respond appropriately to the projected climate change.

Commodity Policies

Agricultural pricing and production policies should promote efficient adjustment to the changing conditions of global supply and demand induced by the greenhouse effect, which may include shifts in comparative advantage among regions and increased likelihood of droughts in some regions. Although these shifts may be slow, the cumulative effects are large and they deserve close monitoring. Market forces as well as government programs will play a crucial role in creating the flexibility to respond to climate changes by sending signals on the efficient use of resources, and in mitigating their ultimate impact as they have done in the past. Agricultural policies should be evaluated to ensure that they are appropriate to both current and future conditions.

Land-Use Programs

Federal legislation aimed at reducing the use of newly plowed grasslands, e.g., the "Sod-Buster Bill," and the related "Swamp-Buster Bill," which restricts agricultural encroachment into wetlands subject to flooding and water-logging, are examples of new policies meant to protect marginal lands. The basic goals of these new laws, which are part of the 1985 Farm Bill, are to protect the most erodible farmland by removing it from crop production and to use conservation as a tool for reducing overproduction.

Another program established in the 1985 Farm Bill that may help alleviate the negative effects of climate change is the Conservation Reserve Program. This program is aimed at removing from crop production the cropland classified as "highly erodible" by the Soil Conservation Service. The bill created a new form of long-term contract of up to 10 years and provides payments to farmers who apply conservation practices, such as maintaining a grass cover, on those acres. If successful, the Conservation Reserve Program may reduce the impact of climate fluctuations on total grain production by taking the most sensitive lands out of use.

The 1988 drought, however, demonstrates that the Conservation Reserve Program may be difficult to maintain in the face of climate stress. As the drought worsened during the summer, use of the set-aside lands was requested so that badly hit farmers could salvage some economic benefits from these acres. Such conflicts may be more common in the future, and land retirement strategies must be weighed against possible needed increases in production in the future.

Awareness of potential changes in agricultural land use due to regional climate change should be built into land-use planning programs, especially in regions where agricultural activities may expand into natural, unmanaged ecosystems. Large-scale drainage and water projects would need environmental impact studies to carefully assess this potential expansion of agricultural land (see Baldwin, Volume _).

Water-Resource Management Programs

Current water supply policies do not generally encourage optimum water-use efficiency. A greater degree of water efficiency should promote flexibility in light of the potential for increased irrigation demands with climate change. Policies such as water transfers and markets should be evaluated for irrigated areas.

Water Quality Policy

The increased use of agricultural chemicals, and changes in the hydrological cycle, threaten both soil and water supplies, and eventually, public health. These effects could be ameliorated by including potential climate change effects in water quality planning and by supporting alternative pest management strategies that use such techniques as biological control, genetic resistance, and innovative cropping systems.

Risk Management

Changes in the frequency, intensity, and location of extreme events are important for agriculture and the regional income that it produces. The adequacy of the private crop insurance and Federal disaster payment programs should be assessed in the face of climatic uncertainty. For example, only about 20-25% of potentially insurable acreage is currently covered by crop insurance. Farmers tend to rely on Federal disaster relief programs to bail them out of such disasters as droughts, floods, hail, and windstorms. Financial risk is also part of the credit structure that covers land, equipment, and production in modern farming.

The frequency and magnitude of climate extremes may be altered with climate change. Responding to the changes may be costly for the government if crops fail frequently. The Drought Relief Bill for the drought of 1988 is scheduled to cost $3.9 billion to cover just 1 year of a climatic extreme. On the other hand, some areas that currently suffer from climate extremes may benefit from climate change. Risk policy mechanisms for relief, recovery, and mitigation of climate change should be examined so that they will be ready to help farmers adjust.

International Trade Agreements

Policies designed to ease the adjustment to greenhouse effects must be global in scope because the effects, although varied, are global in nature. Comparative advantage will shift significantly both within the United States and in other countries. Population and economic activities also will change geographically with climate change, thus affecting the location of demand for agricultural products. It is already a goal of U.S. agricultural policy to incorporate global conditions of supply and demand into the agricultural sector. The potential seriousness of the impacts on the agricultural production system of the greenhouse effect may provide added incentive to establish such policies both nationally and globally. The vulnerability of current and potential food-deficit regions to climate change should also be considered.

Agricultural Contributions to the Greenhouse Effect

Agriculture itself is an active contributor to the greenhouse effect. Clearing of forested land for agriculture often involves burning of trees and shrubs that release CO_2. The biomass that is not burned tends to decay gradually, also emitting CO_2. Agricultural activities release other radiatively active trace gases. Flooded rice fields emit methane (CH_4) as a product of the anaerobic decomposition of organic matter. Ruminants also release methane as a consequence of their digestive processes. In addition, soils may volatilize some of the nitrogenous fertilizer applied to them in the form of nitrous oxide (N_2O). Finding effective ways to reduce these emissions presents a major challenge to the agricultural research community. In this regard, the Conservation Reserve Program and forestation efforts could provide a partial solution, since vegetation fixes CO_2 from the air.

Agricultural Research

The agricultural research community should enhance climate change research from the field level to the national policy level. It should continue to breed heat- and drought-resistant crop varieties and new crop species in preparation for global warming. Research in biotechnology may also be directed toward alleviating the negative effects of climate change. Improved water use and irrigation efficiency also take on renewed importance in the light of potential climate change.

Reduction of agricultural emissions of trace gases also deserves research attention. Development of nitrogen-fixing corn would help decrease fertilizer applications and thus agricultural emissions of N_2O. This would also mean a significant improvement in groundwater contamination.

RECOMMENDATIONS FOR FURTHER RESEARCH

1. Crop productivity -- Study the interactive effects of climate variability and change, CO_2, tropospheric ozone, UV-B from stratospheric ozone depletion, and other environmental and societal variables on agricultural productivity.

   Because of the significant changes in production indicated by these studies, the need for better simulation of the direct effects of CO_2 in the crop models, and the limited adjustment studies performed, further research should be conducted on a longer term basis. Necessary work includes validation of the crop models, resolving the differences in forecasts of the GCMs, and designing more appropriate scenarios including changes in climatic variability. Physiologically based submodels are needed for the effects of increased CO_2 on various crops. The effects on cotton also should be studied because cotton is a major crop, and because daylength may not allow it to shift northward. All the crop models should be improved in their simulation of the effects of increasing temperatures.

Research to this point has provided windows of knowledge concerning certain crops (especially soybeans) at specific stages of their life cycles. Both the direct and the climate change effects of high CO_2 are probably quite different at different stages of development. Research should be performed on the interactive effects of CO_2 and temperature over the whole life cycle of the plant, with realistic conditions of water and nutrition, rather than with "pampered" plants under optimal conditions. Then crop response to the combined climatic and physiological effects of CO_2 may be predicted more realistically.

2. Adaptation strategies -- The dynamic nature of climate change also needs to be studied: What is the rate of adaptation of regional agricultural systems compared to the rate of climate change? Evaluation of the thresholds of sensitivity of U.S. agriculture is needed. Studies should analyze the ability of various aspects of the agricultural production systems to adapt to various rates and degrees of climate change to determine these thresholds of sensitivity.

3. Agricultural economics -- Expand the national analysis to include crops and regions not now included (for example, cotton and grasslands, and pasture in the western regions of the United States). Conduct further analyses of regional implications of shifts in agriculture.

4. International agriculture -- Study the potential shifts in international comparative advantage and the vulnerability of food-deficit regions, and evaluate the implications of such shifts for the United States.

5. Environmental impacts -- Elucidate the impacts of climate change on water quantity, water quality, and other components of the environment caused by shifts in crop and livestock production and related industries.

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CHAPTER 11

THE POTENTIAL IMPACT OF RAPID CLIMATIC CHANGE ON FORESTS IN THE UNITED STATES

FINDINGS

Global warming could significantly affect the forests of the United States. Changes could be apparent in 30 to 80 years, depending upon the region, a site's quality, and the rate of climate change. There may be northward shifts in species ranges, dieback along the southern reaches of species ranges, and changes in forest productivity. The combined effects of climate change and other stresses may exacerbate these impacts. Different migration rates and climate sensitivities may result in changes in forest composition. Large reductions in the land area of healthy forests are probable during this century of adjustment to climatic changes.

Range Shifts

- The southern ranges of many forest species in the eastern United States could dieback as a result of higher temperatures and drier soils. The southern boundary could move several hundred to one thousand kilometers (up to six hundred miles) in a generally northward direction for the scenarios studied.

- The potential northern range of forests species in the eastern U.S. could shift northward as much as 600-700 km (370-430 mi) over the next century. Actual northward migration could be limited to as little as 100 km (60 mi), due to the slow rates of migration of forest species. It could take centuries for eastern forests to fully migrate to potential northern distributions. If climatic change is too fast, some tree species may not be able to form healthy seeds, thus halting migration.

- If elevated CO_2 concentrations substantially increase the water-use efficiency of tree species, the southern declines could be alleviated.

- If climate stabilizes, forests might eventually regain a generally healthy status (over a period of several centuries). In the meantime, declining forests could be subject to increased fires, pest attacks, and replacement with low-value trees, grasslands, and shrubs.

Productivity Changes

- Dieback along the southern limits of distribution of many species could result in productivity declines of 46 to 100

Productivity Changes

- Dieback along the southern limits of distribution of many species could result in productivity declines of 46 to 100 percent, depending on how dry soils become.
- Productivity could increase along the northern limits of some eastern tree species, particularly as slow-growing conifers are replaced by more rapidly growing hardwoods.

Combined Impacts with Other Stresses

- Large regions of severely stressed forests, combined with possible increases in fires, pests, disease outbreaks, wind damage, and air pollution could produce major regional disturbances. These factors were not considered for this study.
- Additional impacts of changes in forests include reductions in biotic diversity, increased soil runoff and soil erosion reduced aquifer recharge, changes in recreation, and changes in wildlife habitat.

Policy Implications

- Institutions such as the U.S. Forest Service, state forest agencies, and private companies should begin to consider how to factor climate change in their long-term planning. Global climate change may need to be a factor in the Forest Service's 50-year plan.
- Strategies that forest agencies may wish to consider include the feasibility of massive reforestation on a much larger scale than practiced now, and the possible introduction of subtropical species into the Southeast in order to maintain U.S. forest productivity. A coordinated public and private reforestation effort, together with development of new and adapted silvicultural practices, may be required. A large reforestation program would also reduce atmospheric CO_2 concentrations, slowing the rate of global warming.

EXTENT AND VALUE OF U.S. FORESTS

Forests occupy 33% of the U.S. land area and exist on some lands in all 50 States. In total, they occupy 299 million hectares (738 million acres) and are rich in such resources as water and wildlife.

Many biotic and abiotic factors influence the condition of forests, but climate is the dominant factor (Spurr and Barnes, 1980). This chapter summarizes what is currently known and predicted regarding the effects of rapid climatic change on U.S. forests.

Distribution and Ownership

Eight major forest regions of the conterminous 48 States contain 84% of the forested ecosystems of the United States (Figure 11-1). The forested areas of Alaska and Hawaii represent the remaining 16% (Table 11-1). Each forest region includes one or more forest types distinguished by the major tree species present. As a general rule, some types in each region have predominantly coniferous tree species (i.e., evergreen, needle-leaved, and softwoods); other forest types are composed mostly of deciduous trees (i.e., tree species that are broad-leaved, have no winter foliage, and are hardwoods). Forest types with a mix of coniferous and deciduous trees, however, are not uncommon.

Superimposed over the natural distributions of trees, forests, and ecosystems in the United States is the human infrastructure. Ownerships include Federal, State, and private lands (Table 11-1). In broad terms, the United States contains public forests (28%), private industry lands (14%), and many small private forests or woodlands (58%) that mostly consist of parcels less than 200 hectares (ha) (about 500 acres) (Woodman, this report). The Federal Government ownership of 40 million ha (99 million acres) of commercial forest lands is primarily in the National Forest System managed by the U.S. Department of Agriculture's Forest Service (36 million ha or 91 million acres); most of the remainder is managed by the Department of Interior's Park Service, Fish and Wildlife Service, or Bureaus of Land Management and Indian Affairs. State ownerships total 9 million ha (23 million acres). Private lands are divided between those of industrial forest companies (27 million ha or 68 million acres) and small landowners, who collectively have 112 million ha (277 acres).

To the degree that all forest lands are owned by some individual or organization, all forest lands are under some form of management. A continuum of management policies exists, ranging from those lands intended to have minimal human intervention, except for protection from catastrophic wildfire (e.g., some parks and most wilderness areas), to lands where silvicultural practices are intensively applied (e.g., the most productive Federal, State, and industrial forest lands dedicated to growing tree crops, Table 11-2). The forests under government and industrial management constitute roughly one-fourth of the

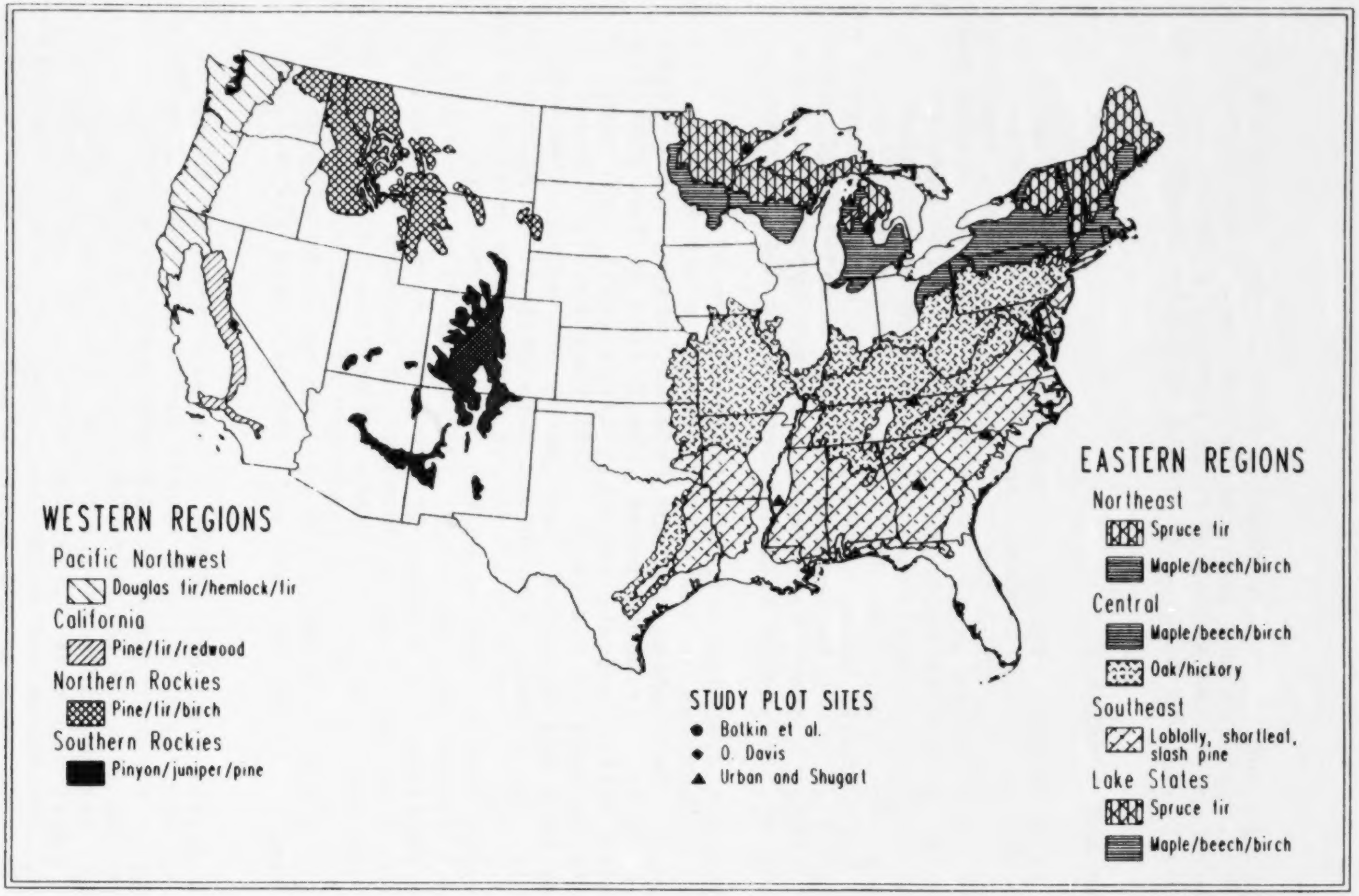
WESTERN REGIONS
Pacific Northwest
Douglas fir/hemlock/fir
California
Pine/fir/redwood
Northern Rockies
Pine/fir/birch
Southern Rockies
Pinyon/juniper/pine
STUDY PLOT SITES
● Botkin et al.
◆ O. Davis
▲ Urban and Shugart
EASTERN REGIONS
Northeast
Spruce fir
Maple/beech/birch
Central
Maple/beech/birch
Oak/hickory
Southeast
Loblolly, shortleaf, slash pine
Lake States
Spruce fir
Maple/beech/birch

Figure 11-1. Major Forest Regions of the Conterminous United States and Their Primary Tree Groups

Table 11-1. Area of U.S. forest lands in 1977 by federal, state, private, and other ownerships (millions of hectares[1]; USDA, 1982).

			Commercial Forests[2]						
					Private				
	Region/States	Primary Tree Species	Federal	State	Industry	Non-Indus	Others[3]	Total	% Total
EAST	Northeast - CT, MA, ME, NH, RI, VT	spruce-fir maple-beech-birch	0.3	0.4	3.9	7.8	0.7	13.1	4.4
	Lake States - MI, MN, WI, ND, SD(E)	spruce-fir maple-beech-birch	2.3	2.8	1.7	9.9	4.2	20.9	7.0
	Central - DE, IA, IL, IN, KA, KY, MD, MO, NB, NJ, OH, PA, TN, WV	maple-beech-birch oak-hickory	1.8	2.0	8.6	22.9	2.6	37.9	12.7
	Southeast - AL, AR, FL, GA, LA, MS, NC, OK, SC, TN, TX, VA	loblolly, shortleaf slash pine	5.8	1.0	14.7	54.3	8.0	83.8	28.1
WEST	Northern Rockies - ID, MT, SD(W), WY	pine-fir-birch	9.1	0.6	0.8	2.7	9.3	22.5	7.6
	Southern Rockies - AZ, CO, NM, NV, UT	pinyon-juniper-pine	6.4	0.3	0.0	2.4	24.1	33.2	11.1
	Pacific Northwest - OR, WA	D. fir-hemlock-fir	7.8	1.2	4.0	3.2	5.3	21.5	7.2
	California - CA	pine-fir-redwood	3.4	.03	1.1	2.0	9.8	16.3	5.4
SEPARATE STATES	Alaska - AK	spruce-hemlock-hardwood	3.3	1.0	0.0	0.1	43.9	48.3	16.2
	Hawaii - HI	ohia	.01	0.2	0.0	0.2	0.4	0.8	0.3
		TOTAL	40.2	9.5	34.8	105.5	108.3	298.3	100
		% TOTAL	13.5	3.1	11.7	35.4	36.3	100	

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[1] Hectare x 2.47 = acres

[2] Commercial forests are those capable of growing at least 1.4 m^3/ha/yr (20 ft^3/ac/yr) of industrial wood materials.

[3] Other forests include county and municiple forests and those federal lands withdrawn from industrial and wood production for use as parks, preserves, and wilderness.

Source: USDA (1982).

Table 11-2. Percentage of Forest Lands by Level of Management Within Four U.S. Regions. (Estimates for 1977

U.S. Region	% Forest Plantations[a]	% Other Commercial[b]	% Reserved/ Deferred[c]
East			
North	9	80	11
South	21	69	10
West			
Rocky Mountains	2	38	60
Pacific Coast	16	44	40

[a] Intensively managed plantations.
[b] Moderately managed forests.
[c] Other commercial.

Source: USDA (1982).

total and might be the easiest to manage under climatic impacts simply because they are larger blocks of lands already under strong management commitments.

Value of U.S. Forests

Most populated regions in the United States are located close to or within a forested region. For instance, the Boston-Washington corridor is within the eastern hardwoods. Atlanta and Southeast populations are interspersed among the southern pine forests. Chicago and nearby Great Lakes communities are surrounded by the mixed conifer-hardwood forests of that region, and the Los Angeles to San Francisco populations parallel the Sierra Nevadas to the east. Forests, therefore, are part of the environmental fabric and general habitability for the majority of U.S. citizens.

All forests shed water to some degree, and two-thirds of the water runoff in the contiguous 48 States comes from forested ecosystems. Precipitation passes through forested ecosystems as canopy throughfall and flows in or along tree stems, the ground surface, and the soil; eventually, some precipitation flows into streams. Water yields from U.S. forests provide about 750 billion liters (200 billion gallons) of water per day for major uses such as irrigation (47%), steam electric (26%), manufacturing (15%), and domestic use (6%). These levels of demand are projected to continue to the year 2030 (USDA, 1981).

A favorite use of forests is outdoor recreation. Activities include hiking, camping, hunting, sightseeing, boating, swimming, fishing, skiing, sledding, and snowmobiling. A 1977 survey of U.S. households indicated that a majority of people participated in outdoor recreation four or more times per year (USDA, 1981).

About 190 million ha (470 million acres), or 64% of the total U.S. forested ecosystems, are highly productive commercial forest lands. These lands represent about 10% of the world's forest area, but they supplied nearly a quarter of the world's industrial forest products in the late 1970s (USDA, 1982). In 1980, 1.7 million people were employed in timber-based occupations across the United States. Such employment is basic to the economic well-being of many small towns and communities (Schallau, 1988). The total value of timber products harvested in 1972 was about $6.4 billion, and the total value after such processes as manufacturing, marketing, transport, and construction amounted to $48 billion, or 4% of the nation's gross national product. In 1979, timber product exports and imports were valued at $7 and 9 billion, respectively. Looking ahead, the consumption of wood products in the United States is projected to increase between current levels and the year 2030 (USDA, 1982).

RELATIONSHIP BETWEEN FORESTS AND CLIMATE

Scientific understanding of forest ecosystems has greatly advanced with each decade of this century. Yet the literature contains little information concerning the direct or indirect effects of climate change on the complex of biological and physical processes in forest ecosystems. Some insights are gained from paleobotanical studies regarding past rates and magnitudes of change during glacial-interglacial cycles, as well as changes in forest composition. Similarly, observations of forest responses to unusual drought or other weather extremes provide some knowledge. Estimates of rate, magnitude, and quality of change have also been derived using computer models developed by plant ecologists or forest management scientists for other objectives. Their validation for understanding how a forest can adapt to climatic change is only in the initial stages.

Climate is a primary determinant of existing forests. The ranges of annual average temperature and rainfall variation determine global forest distributions relative to different biotic regions (Figure 11-2). Substantial increases in temperature or decreases in rainfall could, for example, produce a shift from a forest to a grassland type. Thus, accelerated climatic change resulting from human activities and related effects on U.S. forests is of high concern to citizens and policymakers alike.

Magnitude

As pointed out by Spurr and Barnes (1980), there is ". . . irrefutable evidence that vegetation (i.e., ecosystems) has been in an almost constant state of instability and adjustment due to an almost constantly changing climate over the past 10,000 years and even over the past several hundred years . . . ." Lines of evidence come from studies of fossils, tree rings, carbon-14 dating, plus peat and pollen analyses (Barbour et al., 1987).

Historical climatic changes appear to have been associated with such phenomena as fluctuations in solar radiation, earth orbit variations, and volcanic activity. Evidence of repeated continental glacial advances and contractions in the Northern

Hemisphere dramatically illustrates the large-scale effects of global climatic change.

In response to the glaciation, ecosystems shifted south. Evidence from fossil pollen, for example, indicates a southward shift of spruce into Georgia and east Texas during the last glacial advance and treeless tundra in the Great Lakes States (Spurr and Barnes, 1980). During the maximum interglacial warmth of 6,000 to Figure 11-2. Approximate Distributions of the Major World Bioass Based Upon Mean Annual Temperature and Precipitation (Hammond, 1972) 9,000 years ago, which was 1.5°C (2.7°F) warmer than the present temperature level, plant zones were one to several hundred km (60-250 miles) north of present distributions.

Rates

All forested ecosystems experience change on both spatial and temporal scales; each biological and physical forest component may respond to climatic variation on different spatial and temporal scales. For example, microorganisms, insects, and birds come and go with relatively short-term climatic variation; shrub species abundances vary within the timespan of decades; trees, once established, could persist for centuries. This understanding is important from the perspective of climatic change, since it implies that forested ecosystems do not respond as a unit, but in terms of parts. Different parts respond differently; consequently, future forested ecosystems under a rapidly changing climate could be quite different from those existing today.

At the expected rapid rate of climatic change, the potential rates of forest migration would become a major concern. Migration rates vary by species. Paleorecords of the Holocene (10,000 years ago to present) show that extension of ranges for tree species of eastern North American (in response to glacial retreat) varied from 10 to 20 km (6 to 12 miles) per century for chestnut, beech, maple, and balsam fir (Zabinski and Davis, this report). Other species within the oak and pine groups extended at faster rates, i.e., 30 to 40 km (19 to 25 miles) per century.

Mechanisms

Knowledge of causal links between weather patterns and forest response is fundamental to projecting growth and composition effects resulting from climate change. Another requirement is to understand the climatic influences on population processes of forest plants and animals. These include such phenomena as fires, windstorms, landslides, pest outbreaks,

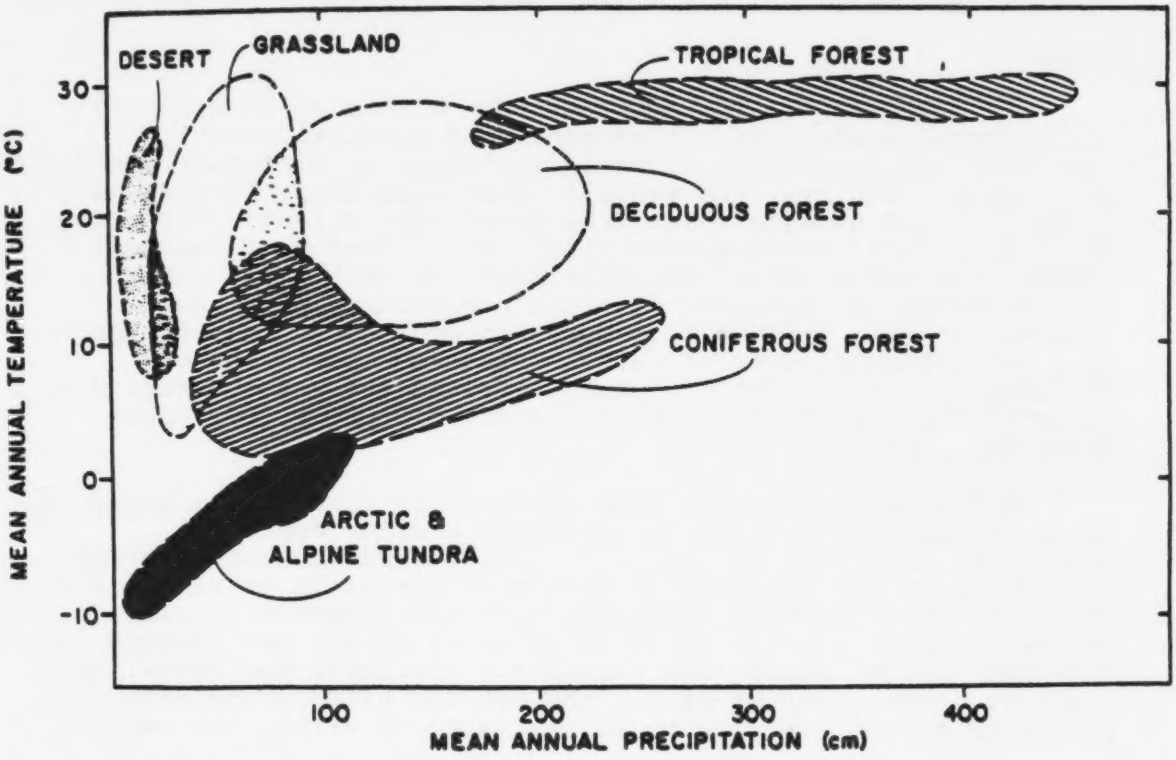


Figure 11-2. Approximate distributions of the major world bioass based upon mean annual temperatures and precipitation

Source: Hammond, 1972.

and other disturbances that affect survival and subsequent colonization by different species. Furthermore, the processes that control the dispersal of seeds through a mosaic of different ecosystem types (such as forest patches interspersed with agricultural lands, wetlands, grasslands, and other land-use groups) must be clearly defined.

Among the important factors now known to influence the growth and distribution of forests are the following.

Temperature

The optimum temperature for growth depends upon the tree species and other conditions. Warmer temperatures usually increase the growth of plants. However, very high temperatures decrease the growth of plants or kill those growing at optimum (or higher) temperatures. Cold temperatures can limit plant distributions by simply limiting growth at critical stages or by directly killing plants.

Precipitation

Too much or too little precipitation can limit forest production and survival. Too much rainfall in some areas can cause flooding or raise the water table, thus drowning roots that require oxygen or promoting fungal attack. Too little rainfall can reduce growth, cause susceptibility to fire or pestilence, and possibly kill plants. The seasonal timing of rainfall is more important than total annual rainfall, although forests also require some minimum total annual rainfall (see Figure 11-2).

CO_2 Concentration

High CO_2 concentrations could increase tree growth through increases in photosynthesis rates and water-use efficiency (primarily hardwood species) when water and other nutrients are not limited (Strain and Cure, 1985). Plant responses to CO_2 have been investigated largely in growth chambers and are difficult to extrapolate to the real world. Responses are varied and do indicate some measure of adaptive capability most likely imparted from ancestral exposure to much higher and lower levels in the geologic past. However, in natural situations, water nutrients or temperature usually are limiting factors in forest growth, thus making the impacts of CO_2 enrichment uncertain. If water use efficiency increases, then tolerance to drought might increase, ameliorating declines in southern parts of ranges. Unfortunately, the current state of knowledge does not allow generalizations on this subject.

Light

The amount of sunlight bathing an ecosystem sets the upper limit on net primary productivity. Thus, the tropics exhibit higher productivity than do the boreal regions. This potential productivity would, of course, be limited by other climatic effects such as drought, cold, heat, and natural disturbances, and the time required for forests to shift into new ranges. The length of day exerts considerable control on physiological processes such as release from and onset of dormancy. Significant northward shifts of forests would alter their day length regime, producing uncertain results.

Nutrient Status

In addition to climate, most forest growth is strongly influenced by availability of soil nutrients. Disturbances over vast regions, such as by drought followed by fire, can release large quantities of essential nutrients into the atmosphere and surface waters and can make soils deficient. Lengthy periods of soil development are usually required to replenish the soil nutrients before a large, mature forest stand can be supported. In turn, soils reflect properties of the forests that they support. This results from decades of nutrient uptake, litterfall, decomposition, and other processes.

Atmospheric Chemistry

Much of the nutrient budget of forests involves deposition of chemicals from the atmosphere as gases, aerosols, particles, and in solution. Although most of these act as nutrients, some produce acid deposition that can leach important soil nutrients (e.g., $SO_4^=$), produce a fertilizing effect (e.g., NO_3^-), or damage leaf tissue (e.g., O_3). Climatic change will alter transport paths of air pollutants, and increased temperature could increase the rates at which gases convert to deleterious forms.

Disturbances

Almost continually, forests experience natural disturbances or stresses from biotic or abiotic agents alone or in combination. Examples are insects and disease outbreaks, plant competition, wildfire, drought, cold extremes, and windstorms.

These disturbances, which are among the primary factors controlling the successional processes in forests (Pickett and White, 1985), may range from an opening of small gaps in the canopy as the result of single tree death or of windthrow occurring when trees are blown down by heavy winds (predominant successional mechanisms in eastern hardwoods), to large clearings from fire, windthrow, or pestilence (predominant successional mechanisms in western forests).

Landscape Processes

The horizontal movement of material and disturbances through the landscape is critical to the processes controlling forest migration, species diversity in forests, and the spread of fire, windthrow, and pestilence effects. These processes are very poorly understood; quantification in the emerging field of landscape ecology is just beginning.

Multiple Stresses

In general, trees or forests stressed by one factor, e.g., accelerated climatic change, are more susceptible to natural stresses (secondary disturbances) such as insects, disease, or invading weed species. The concept of multiple stresses leading to forest declines is becoming more widely recognized (Manion, 1981). Regional climatic changes, even if temporary, frequently predispose forests to damage by other natural or anthropogenic stresses.

PREVIOUS STUDIES ON THE NATIONAL EFFECTS OF CLIMATIC CHANGE ON FORESTS

Concern regarding effects of climatic change on U.S. forests has prompted several excellent reviews. One of the most comprehensive (Shands and Hoffman, 1987) was the result of a conference sponsored by EPA, the National Forest Products Association, and the Society of American Foresters. While pointing out the high uncertainty associated with current predictions of climatic change, several authors suggested that if predictions are true, distributions of key forest species in the United States will change significantly.

Other recently produced compilations broadly consider forest effects, such as in agriculture, prairie land, and the Great Lakes (White, 1985; Titus, 1986; Meo, 1987; Tirpak, 1987). These reviews are largely pioneering efforts and some overlap occurs, but each presents some key points.

The methods used in the previous studies are quite similar to those used in this report. They include computer modeling of forest processes, literature surveys, studies of fossil evidence, and empirical relationships constructed by experts. The estimates of future change produced from these studies are generally based on the output of one or more of the General Circulation Models used for this report. Thus, the results of the previous studies are consistent with those reported here.

STUDIES IN THIS REPORT

Six studies on forest effects contributed to the regional case studies reported in this volume. The purpose was to use existing methods and data bases to protect U.S. forests from predicted climatic change. The selection of the six studies was based upon three criteria: use of available technology; testing hypotheses focusing on causal mechanisms; and a mix of studies that complemented each other, such that the strengths in one approach might overcome the weaknesses of another.

This report focuses primarily on forests within the lower 48 States. It is worth noting, however, that the largest magnitude of warming is expected in the northern latitudes encompassing the boreal forest and other forest types in Alaska and Canada. These large forests could be under significant risk from climatic warming.

Study Design

Characteristics of the six studies are briefly listed in Table 11-3. With the exceptions of the Overpeck and Bartlein study and the Woodman study, the methods are discussed in the regional case study chapters and will be mentioned only briefly here.

Two studies used correlations between tree distributions and climate (Overpeck and Bartlein; Zabinski and Davis). Overpeck and Bartlein's approach consists of correlating the modern pollen distributions of important tree species with January and July mean temperature and annual rainfall. The correlation is then tested by reconstructing past pollen distributions from General Circulation Model simulations of past climates (during the most recent glacial-interglacial cycle) for each species and comparing them to observed pollen distributions from those periods. Future pollen distributions are then constructed from the expected doubled CO_2 climate projected from the different model climate scenarios. The correlations are constructed on modern pollen distributions, rather than tree distributions, to allow the direct comparison to fossil pollen data. Modern pollen distributions are similar to, but not exactly the same as, modern

Table 11-4. Principal Investigators, Regional Focus and Method of Approach for the Regional Forested Ecosystem Studies

Principal Investigator	Region	Method
Overpeck and Bartlein	Eastern North America	Correlation and fossil studies
Urban and Shugart	Southeast Uplands	Forest dynamics model
Botkin et al.	Great Lakes	Forest dynamics model
Zabinski and M. Davis	Great Lakes	Correlation
Davis	California	Fossil studies
Woodman	Southeast, California, and National	Literature review

tree distributions. The verification studies indicate that the approach works reasonably well at a coarse spatial resolution. That is, northern trees are in the north and southern trees are in the south, with the regional patterns being reasonably well represented.

The approach of Zabinski and Davis is essentially the same as that of Overpeck and Bartlein, except that the correlations are constructed from the actual modern tree distributions rather than from the modern pollen distributions (see the Great Lakes chapter of this report).

Two of the studies used computer models of forest dynamics (Botkin et al.; Urban and Shugart). Both studies explored forest response on a range of soil types from well drained to poorly drained. Forest growth simulations from bare ground represent conditions after a fire, logging, or similar disturbance. Mature stand simulations are useful for investigating the potential response of present forests to gradual climatic change in the immediate future.

For the California case study, Davis reconstructed vegetation patterns in the Sierra Nevadas from fossil pollen studies for the interglacial warm periods between about 6,000 and 9,000 years ago. These reconstructions represent possible analogs of a future warm period at the lower magnitude of the predicted future warming.

A literature review was conducted by Woodman for the Southeast and California forested regions and peripherally for the nation as a whole. The purpose was to ascertain the attributes of the forest resource in terms of extent, ownership economic and recreational value, and policy considerations.

Study Results

The six studies conducted by EPA are consistent enough to indicate that climatic changes would significantly affect the natural forests of the United States. The distribution of healthy forests in the eastern United States appears to become greatly reduced from their areas during the next century (see Figure 11-3 and 11-4). This results from a very slow northward migration coupled with a fairly rapid decline in the southern and western parts of species ranges. Drier forest conditions in the United States, induced as much by increased temperature as by changes in rainfall, would mean less tree growth and therefore reduced forest productivity in general.

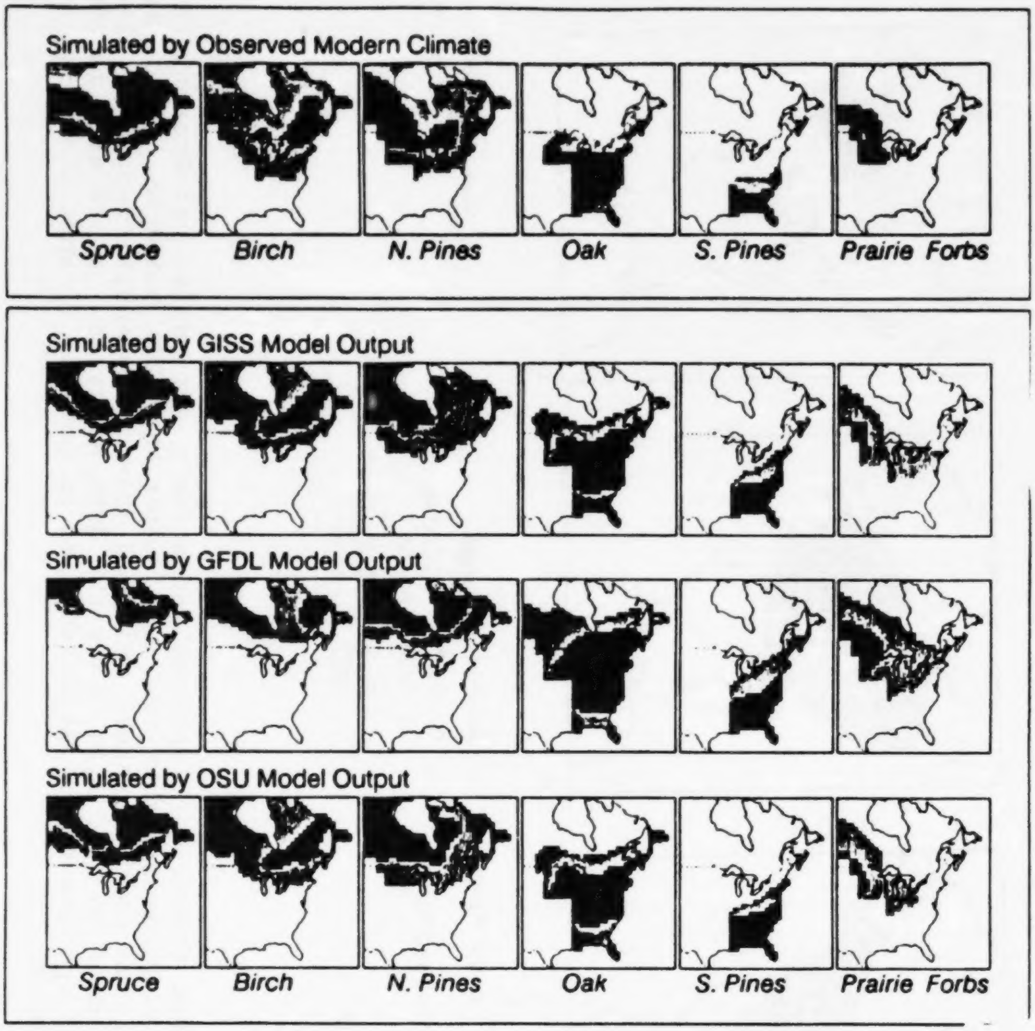

Simulated by Observed Modern Climate
Simulated by GISS Model Output
Simulated by GFDL Model Output
Simulated by OSU Model Output
Spruce
Birch
N. Pines
Oak
S. Pines
Prairie Forbs

Figure 11-3. Present distribution of major forest genera and herbs vegetation of eastern N. America compared to potential future distributions after reaching euilibrium with the climate predicted for $2xCO_2$. The comparison is based upon simulated modern pollen data (a) and simulated future pollen abundances for each of the three $2xCO_2$ scenarios: (b) GISS; (c) GFDL; and (d) OSU (Overpeck and Bartlein, Volume _).

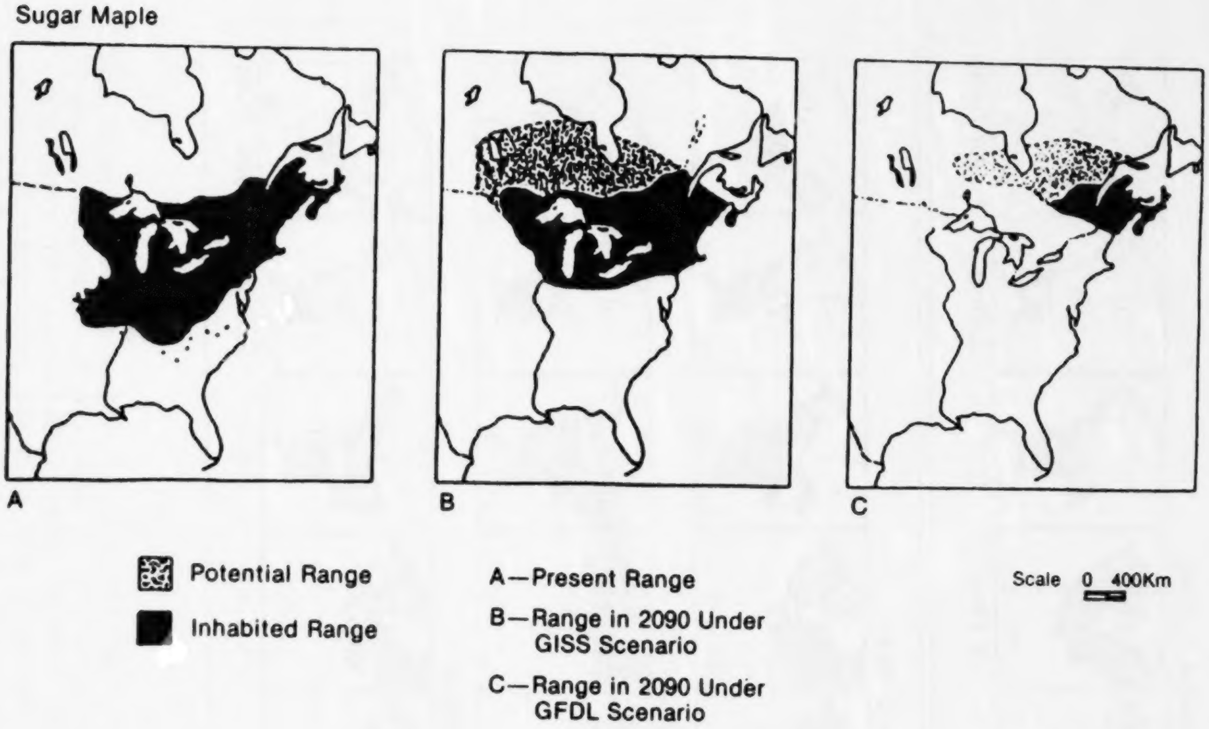

Sugar Maple
A
B
C
▨ Potential Range
■ Inhabited Range
A—Present Range
B—Range in 2090 Under GISS Scenario
C—Range in 2090 Under GFDL Scenario
Scale 0 400Km

Figure 11-4. Present and future geographical range for sugar maple. a: Present range. b: $2XCO_2$ climate-space in 2090 A.D. under the GISS scenario. Black area is the predicted species range; stippled area is potential range. c: $2XCO_2$ climate-space in 2090 A.D. under the GFDL scenario. Black area is the predicted species range, stippled area is potential range (Zabinski and Davis, Volume _).

The forest simulation models provide an indication of the importance of uncertainties imparted by the climate scenarios. The climate scenarios differ primarily in their representation of regional rainfall patterns. The model results indicate that temperature has a large effect on forest health, either directly through cold and heat stress or indirectly by exaggerating drought effects. Thus, the overall characteristics of forest responses are remarkably similar among the three climate scenarios.

Magnitude

Eastern Forests - Northern Limits

All of the study results suggest a northward expansion of most eastern tree species (Figure __ displays results from Overpeck and Bartlein). That is, spruce, northern pine, and northern hardwood species would move north by about 600-700 km (375-440 miles) into the Hudson Bay region of the Canadian boreal forest (Overpeck and Bartlein; Zabinski and Davis). New England coniferous forests would be replaced by more hardwood forests and especially by the oak species from the eastern mid-United States (Botkin et al.; Overpeck and Bartlein; Zabinski and Davis). As the northern mixed forests shift from spruce-fir to sugar maple, some sites could actually triple their present productivity (Botkin et al.).

Additionally, southern pine species could shift about 500 km (310 miles) into the present hardwood forest lands of eastern Pennsylvania and New Jersey (Overpeck and Bartlein; Urban and Shugart; Solomon, 1986; Miller et al., 1987). Depending upon the severity of climate change, Urban and Shugart estimate that near the northern limits of slash pine in East Tennessee, above-ground woody biomass in 100 years could range from little change to extremely low biomass with no trees supported (i.e., a grassland, savanna, or scrub). However, even with little decrease in productivity, species shifts would alter the forest composition from shortleaf to loblolly pine, a more commercially valuable tree species.

Eastern Forests - Southern Limits

Ultimately, forest decline and mortality could truncate southern distributions of tree species by as much as 1,000 km (625 miles) in many northern hardwood species (Zabinski and Davis; Overpeck and Bartlein) or by as little as a few hundred km (60 miles) in southern pines and hardwoods (Urban and Shugart; Solomon and West, 1986). Under the driest scenario, Zabinski and

Davis predict local extinction in the Great Lakes region of many eastern tree species such as eastern hemlock and sugar maple (Figures 11-3 and 4). These estimates bear considerable uncertainty for all species.

These uncertainties are particularly true for the southern limits of southeastern species that border the continental margin. The actual southern climatic limitations of these species are not well known (Urban and Shugart). Nevertheless, under the most severe climate scenario in the Southeast with increased temperatures and decreased growing-season precipitation, Urban and Shugart's results suggest that the 18 tree species they considered would no longer grow in the southern half of the region. Present forest lands in the region would be replaced by scrub, savanna, or sparse forest conditions. Under the most mild scenario, much of the southern half of the Southeast would not support trees, and areas in South Carolina would be marginal, supporting about half the current biomass of forest.

Biomass accumulations in 100 years for mature natural forests in productive sites in the Lake States could be reduced to 23-54% of their present values (Botkin et al.; Solomon and West, 1986). On poor sites, forests could be converted to grassland or savanna with very low productivity, ranging from 0.4 to 28% of their present values.

Western Forests

Similar projections were made for six western coniferous species: ponderosa and lodgepole pine, Douglas-fir, western hemlock, western larch, and Englemann spruce (Leverenz and Lev, 1987). Predictions are mixed for the West. Because of the mountainous conditions in the West, upslope shifts are possible for Douglas-fir, ponderosa, and western hemlock in the northern Rocky Mountains. In the coastal mountains of California and Oregon, Douglas-fir should shrink in the lowlands and be replaced by western pine species (Davis, this volume; Leverenz and Lev, 1987). Overall, the western forest lands are predicted to favor more drought-tolerant tree species, such as the hard pine group, at the expense of fir, hemlock, larch, and spruce species.

If regional drought persisted, the frequency of fires could increase, significantly reducing total forested area. Also, with massive upslope movement, some species would be pushed off the tops of mountains into local extinction.

No quantitative estimates have been derived for productivity for the western forests under potential warming conditions. However, using the analog approach of Davis, under the most severe conditions projected for California, the species composition of the west-side Sierra Nevada forests would become more similar to that of the east-side forests. This would reduce the standing biomass to about 60% of current levels.

Rates of Decline and Migration

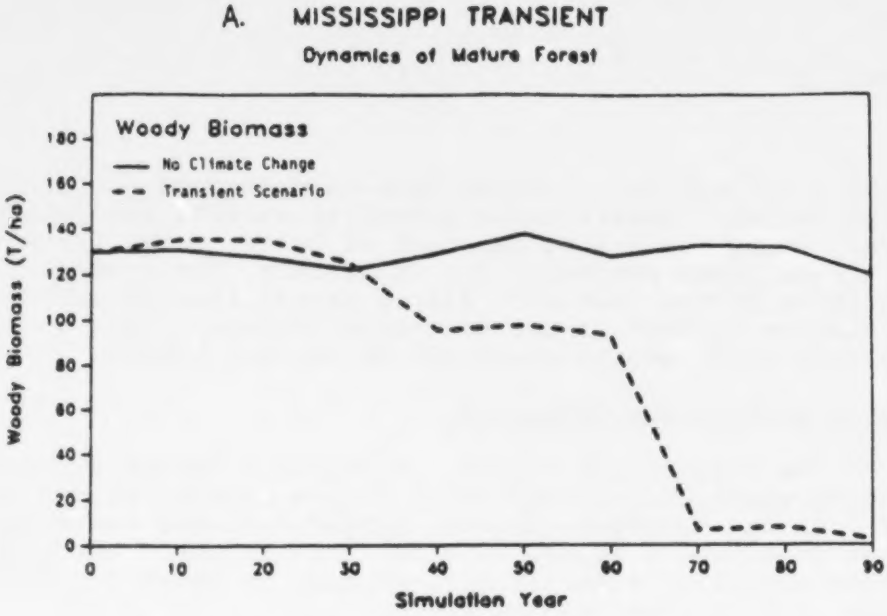
In the Great Lakes region, significant forest decline and forest compositional change could become evident within 30 to 60 years. In the Southeast region, forest declines could become evident in 60 to 70 years, with declines in the drier western portions occurring even earlier, perhaps in about 30 years (Figure 11-5) (Urban and Shugart).

These rapid declines, coupled with the expected magnitude of change, raise the question of how fast forests can migrate. Based upon fossil records, Zabinski and Davis have estimated that the maximum dispersal rate of several tree species in response to the last glacial retreat was roughly 50 km (30 miles) per century. Under the expected rapid warming, they estimated that a dispersal rate of about 100 km (600 miles) per century would be required to maintain species distributions near their current extent. Such migration routes are doubtful, suggesting greater reductions in species ranges under rapid climatic changes.

Mechanisms of Migration

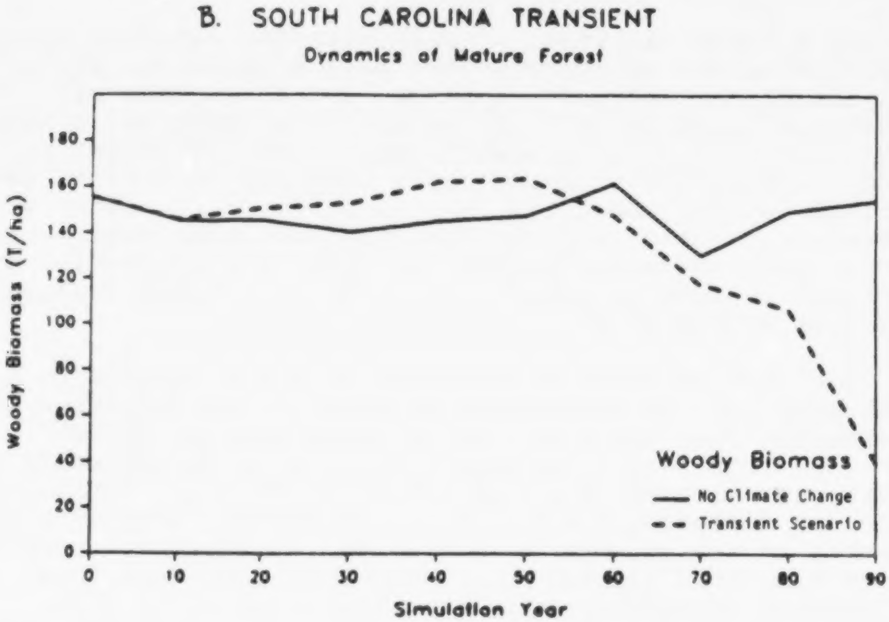
Distribution changes suggested by these studies (i.e., migrations) must be considered carefully. Reproductive processes are essential for the migration of tree species across the landscape. For many tree species, climatic change could reduce natural regeneration in an existing location and introduce the species at different latitudes or altitudes. Reproductive processes in trees, such as flowering, pollination, seed set, seed germination, and seedling competitive success, are particularly sensitive to climate.

Specific regional climate scenarios vary as a function of the GCM. All scenarios predict increases in temperature; however, some predict increases in rainfall, and others predict decreases. The northward shifts of species appear to result from a release from cold temperature stress, which normally freezes flowers, seedlings, and even adult trees. However, the western and southern limits of eastern tree species appear to result from insufficient moisture stress and excessive heat stress, which



A. MISSISSIPPI TRANSIENT

Dynamics of Mature Forest



B. SOUTH CAROLINA TRANSIENT

Dynamics of Mature Forest

Figure 11-5. Projected changes in biomass (T/ha=2.24 t/acre) of mature forests in Mississippi (A) and South Carolina (B) under the GISS transient climatic change scenario (Chapter __; Urban and Shugart, Volume _), shifts toward drier conditions and the prairie advances to the East. Presumably changes in western forests would result from similar mechanisms. The drought-induced declines in forests might be partly offset if CO_2-induced increases in water-use efficiency were realized.

primarily affect sensitive life history stages but can also affect adult trees.

All of the study approaches used under all of the climatic scenarios predict major forest declines in the southern parts of species ranges and expansions to the north. These declines, resulting primarily from drought stress, would occur despite the differing rainfall predictions. Increases of temperature would severely reduce water intake, and therefore, would produce drought. Although precipitation could increase slightly in some U.S. locations, generally the increased evaporative demand caused by higher temperature would be a greater factor. Subsequent differences in rainfall between the various climate scenarios would modify the magnitude of regional drought patterns. The western limits of eastern forests could similarly retract as the climate. Existing forests probably would not shift intact, but would change in composition. Variations in migration rates and sensitivities to weather variables produce individual responses to climate change. These changes are consistent with the well-known dynamic nature of ecosystems and were projected for the forests of all regions. In the Great Lakes region, for example, beech would decrease in abundance, and birch and maple would increase (Zabinski and Davis; Botkin et al.). On some lands, forest productivity could remain about the same as today, but changes to less economically important species could be significant.

Not considered quantitatively in any of the studies are changes in forest disturbance regimes. These changes should not be considered lightly. Extreme and more frequent climatic variations (see Chapter 17) could cause much higher mortality in U.S. forests than the current experience. Although little is known as yet, some locations may experience an increase in the frequency of extreme weather events, for example, wind, ice, or snow storms, droughts, and flooding. Besides the direct damage these events can cause, they can cause drainage from insects, disease, and wildfires.

Study Limitations

Although predicted effects vary, these six analytical studies have results that are collectively consistent enough to advance our knowledge and justify concern regarding the future of U.S. forests under rapid climate change. The range of predicted effects is large; however, uncertainties exist regarding (1) the climate scenarios; (2) the kind and rates of responses of individual tree species; and (3) changes in forested ecosystems as a whole from environmental change. All of these factors significantly influence the precision and accuracy of the results.

A major uncertainty in the simulation model approach involves the rates of species dispersal into a region. The current generation of models has no dispersal mechanisms. A species is simply present or it is not present. For example, Botkin et al. excluded more southern tree species so that their dispersal was unrealistically nonexistent, and these southern species could never enter the region. But if they had been included in the simulations, these species would have entered the northern forests at the same rate as the climate change. This would have assumed dispersal rates far in excess of reality. This limitation can, in part, be overcome by studies, such as those of Zabinski and Davis, that provide some insight into actual dispersal rates and species migration.

The models also carry assumptions about the environmental controls of species limits. In most cases these assumptions are reasonable, given that the assumed control (for example, July temperature or annual rainfall) is usually related to the actual control, perhaps accumulated warmth or summer drought. However, large uncertainties exist in some instances. This is particularly true with regard to the climatic controls of the southern limits of southeastern forests, simply because of their association with the continental margin. Does the climate at that latitude represent the actual climatic limitation to the distributions, or are the species simply stopped by a geographic barrier? No one really knows. These uncertainties were partially addressed by Overpeck and Bartlein, who compared their fossil pollen approach to the modeling approach. The two approaches use similar relations to climate. Both approaches can be used to simulate forest distribution in the geologic past and both do reasonably well.

Several uncertainties with the pollen-climate correlation approach limit its precision and accuracy. First, many of the plant taxa used in the study are plant genera (e.g., pine, oak) rather than species, and thus the simulated results are not taxonomically precise. Second, the results are applicable only on a regional scale; local scale predictions are not made. Third, and very significant, the simulated results assume that all the plants are in equilibrium with the new climate. Rates of dispersal vary between species, and several hundred years may pass before plant communities are again in equilibrium with climate. How this lag would affect vegetation dynamics is not addressed in this study and is an important research question.

The paleoecological analysis of the past vegetation in the Sierra Nevadas (Davis) presents several uncertainties. First, differences with respect to weather variations (i.e., season to season and year to year) could produce strikingly different types of vegetation. Also, there is a large uncertainty about what the most appropriate analog period might be -- or if one even exists! Furthermore, the rate of climatic change in the future is predicted to be much faster than the rate of climatic change during the past 20,000 years. Lags in the response of species to the future climate could strongly affect the type of forest at any one location, whereas in the past, with a more slowly varying climate, lags in species response were not as important in determining forest composition. To the extent that climatic regimes predicted for the future are similar to the climates of certain periods in the past, a picture of future forests can be estimated from these past periods.

All of the studies are deficient in some very important processes controlling forest responses to climate, particularly disturbance regimes such as fires, windstorms, hurricanes, landslides, and pest outbreaks. In addition, the responses of mature trees to elevated CO_2 under conditions of moisture, temperature, or other nutrient limitations remain largely unexplored. Most research on elevated CO_2 on plants has been performed in controlled chambers using seedlings (Strain and Cure, 1985). However, the seedlings were not previously grown in or acclimatized to high CO_2 environments. Evidence has shown that plants grown under high CO_2 will respond much differently to changes in temperature, light, and moisture conditions (Strain and Cure, 1985). However, our ability to extrapolate CO_2 fertilization results from laboratory experiments to the natural world is limited, and our understanding of regional changes in water use efficiency is even less. Furthermore, complex interactions between fertilization effects and changes in water use efficiency can produce unexpected problems such as reduced heat tolerances due to effects on evaporation cooling. These interactions are least understood, but could produce major regional changes in forest responses. Therefore, it is not yet possible to quantitatively incorporate the direct effects of CO_2 on forests into studies such as these. Further, if water or nutrients are limiting to forest growth, then the effects of carbon fertilization may not be significant.

NATIONAL, ECOLOGICAL, AND SOCIOECONOMIC IMPLICATIONS

The effects of the predicted climate changes resulting from a doubling of CO_2 by 2030 may be considered from two perspectives: ecological and socioeconomic. Evidence for significant national implications is strong from both viewpoints.

Ecological Implications

Ecological implications for forests commonly start with tree response. But strong implications also exist in regard to other ecosystem components, e.g., animals, soils, water, secondary impacts, and as noted, the atmosphere through which climate change is mediated. Forest effects are described in terms of tree distribution changes and biomass production changes, but among the other major components, there is a host of interacting processes. Thus, significant changes in tree response would be accompanied by ecological reverberations throughout all the forested areas of these regions.

Tree distributions and biomass productivity

Forest migrations to the north in response to rapid warming in North America during the next century will be likely. However, significant lag is possible. Even under the maximum rates of species dispersal estimated by Zabinski and Davis, healthy forest areas may not redevelop for several centuries. Meanwhile, forest decline would not be under such constraints, so the extent of healthy forested regions in the United States probably would be greatly reduced. Though some locations may have increased productive potential from a biomass per hectare standpoint, the large reductions in areas with healthy forests would likely create a net reduction in forest productivity for the United States for several centuries.

Even if a massive reforestation effort were undertaken, the new forests resulting from species shifts may or may not be as productive as existing forests. More northern latitudes or higher elevations raise other considerations. Farther north, days are longer in the summer and shorter in the winter. At higher elevations, damaging ultraviolet light intensity is greater. All of these conditions could lower forest productivity below optimum and could hinder reproduction and survival.

Animals

A change in the size and relative homogeneity of forests could influence whether some animals can continue to live in habitats to which they have adapted.

Depending upon the species, animal migration can be hindered by boundaries between forests and other land types or facilitated as animals move along edges. In turn, some animals prefer young forests, and others prefer old forests. Some animals can exert a profound influence on forest structure and composition through selective browsing of seedlings, insect attack of different tree species, and other effects. All of these factors combine to influence the regional patterns of biotic diversity of both plants and animals (see Chapter___).

Soils

Soils under warmer climates also would change, though at a much slower rate than shifts in species distribution. Optimum soil conditions for high forest productivity supporting species at more northern latitudes or higher elevations might take several centuries to develop. Furthermore, it is not at all clear that some northern soils could even support more southerly species. The soils of the boreal forest are vastly different from those under the deciduous forests to the south.

Water

Where forests give way to drier conditions (e.g., in the Great Lakes and California), many lands now serving as watersheds might be used for a different purpose. Furthermore, regional-scale disturbances (such as fire) and applications of chemicals (such as fire retardants, fertilizers, and pesticides) could degrade regional water quality and increase airborne toxic chemicals (see chapter on Water Resources in this report).

Sea level rise is an additional water impact related to some forests. Projections for sea level changes are up to 1 meter (3 feet) in the next century (see Sea Level Rise chapter in this report). Many forest lands of high value for timber production (e.g., in the Southeast) or recreation (in the Northeast, Northwest, and California) are close to ocean coasts. Inundations, decreases in depth to the water tables, and saltwater intrusions could trigger rapid forest declines near these areas.

Secondary Impacts

As the southern bounds of forests tend to shift north, forest decline (sick and dying trees) could become extreme over vast areas. These areas would be highly susceptible to weed competition, pest outbreaks, or wildfire. As forests decline, species of lower economic value such as chokecherry, as well as weedy shrubs and herbs, could invade via wind dispersion. Under stressful environments, such species are severe competitors to most commercial tree species.

Trees experiencing less favorable growth conditions are more stressed and will be vulnerable to insect and disease attack. These secondary pest impacts could last "until the most vulnerable forest stands or tree species are eliminated" (Hedden, 1987). In addition, the incidence of catastrophic wildfires is predicted to increase in U.S. forests with higher temperatures. Simand and Main (1987) estimated an 8% rise in the occurrence of fires and a 20% increase in fire-suppression costs.

Socioeconomic Implications

The United States enjoys substantial economic and cultural benefits from its forests. Until recently, the nation's forest managers assumed that these benefits could be sustained by maintaining forests in a healthy condition (Fosberg, 1988). This was achieved, for example, by preventing fires or pest invasions, avoiding careless use, and enhancing productivity through good silviculture.

Beginning with the possibility of damage from regional air pollution damage to forests, suspected in the 1980s, alterations of the environment external to forests presented a new concern. Research and policy discussions to deal with this issue are ongoing.

If climate changes as rapidly as predicted, this additional external influence with its more global dimensions looms as a possible hazard to forests and their use. As can be imagined, a list of potential socioeconomic concerns would be large. To provide a brief perspective, three issues are considered.

Quality of the Human Environment

The forest amenities enjoyed by most U.S. citizens will be affected according to different forest responses. In the Boston-Washington corridor, a composition change from predominantly hardwood to more pine forests, though ecologically significant, would probably only superficially affect most people. In the Atlanta-Southeast region, the southern pine forests, while undergoing a gradual expansion of their northern boundaries, would have less vigor in the remaining stands. This could raise their vulnerability to damage by insects and disease, reducing esthetic values -- at least an intermediate impact for most of the local citizens. In contrast, drier climates in the Great Lakes and California regions may cause the loss of some forest lands to prairie or desert conditions, respectively -- a severe change for the people there, not only in their living environment but also in the whole spectrum of forest land use.

Recreation

Forests must be in a relatively healthy condition to support quality recreational use (Clawson, 1975). Forests undergoing gradual composition changes might remain healthy, but rapid changes would most likely cause stressed or declining forests. Such forest conditions would have less recreational appeal because of such factors as less pleasing appearance, greater threat of wildfire, and reduced hunting quality when game populations change or are diminished. Furthermore, drier conditions in U.S. forests would harm recreational opportunities that depend on abundant water or snow.

Wood Products

Altered U.S. forest productivity resulting from climatic change would have obvious major economic impacts. Significant yield reductions could lead to unemployment, community instability, industrial dislocation, and increased net imports of wood products.

Reforestation projects could make up for some losses in forest productivity and artificially advance migrations forced by climatic change. Reforestation technology has greatly improved in recent decades so that success rates also have increased greatly. Examples are high-vigor seedlings through improved nursery practices, genetic selection, and tissue culture. Improvements in the field include machine planting, fertilization, and weed control on selected sites. Results are evident from the large acreages of plantations established in the United States in recent decades, particularly with loblolly pine in the southeast and Douglas-fir in the Pacific Northwest (see Table 11-5).

Innovative manufacturing trends should prove to be timely during times of rapid forest change. High-strength and durable products from reconstituted wood (e.g., new particle board concepts, warp-proof hardwood lumber, paper products of fiber from multispecies) are now in use or well along in development. These new methods will lessen the present overdependency on a few commercial conifer species from stands above minimum size and quantity (Ince, 1987). The result will be an ability to use the timber resources of the future, however they change in composition.

Table 11-5. Levels of management within U.S. forests in 1977 as illustrated by areas in three broad uses within four major regions. Intensively managed are represented by plantations[2]; moderately managed are those forests naturally established but with commercial rates of growth[3]; and forests with protection as the primary level of management (i.e. deferred or reserved[4]; estimated from tables 3.1 and 9.2, USDA, 1982).

U.S. Regions	Management level (millions of hectares[1])			
	Intensive	Moderate	Protected	Total
East				
North	3	65	4	72
South	8	69	7	84
West				
Rocky Mountain	1	23	32	56
West Coast (WA, OR, CA)	3	22	13	38

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1. Ha x 2.47 = acres

2. Plantations are forests established by seeding or planting, generally on the most productive lands, and followed by silvicultural tending such as thinning, fertilization and weed control until harvest at an economically optimum age.

3 and 4. Definitions in Table 11-1.

Chapter 11

NATIONAL FOREST POLICY AND CLIMATIC CHANGE

Historically, U.S. forest policies have undergone continued development to meet national change (Young, 1982). The earliest policies were adapted by the New England colonies in the 1600s to regulate overculturing near settlements. Wood was needed for fuel and buildings, but existing methods were not capable of long distance log transportation. Development of U.S. forest policies continued and has been particularly intense this century, as the National forests, National parks, and wilderness areas were established.

At present, forest managers are dealing with many additional policy issues. Five of these (Clawson, 1975) are important to climatic change/forest response:

- How much U.S. land should be devoted to forests?
- How much forest land should be withdrawn from timber production and harvest?
- How should the Federal forest lands be managed? (That is, the lands under the USDA Forest Service, USDI Park Service, Bureaus of Land Management and Indian Affairs, etc.)
- What constraints (e.g., mandatory forest practices) should be placed on forest managers to ensure national environmental goals?
- Who should pay the additional costs incurred in implementing new policies?

The large array of forest ownerships in the United States makes development and implementation of forest policy more complicated than in most countries, where nearly all forests belong to the government. The diversity of owners and managers results in widely divergent goals and objectives.

How Much Land Should Be Forested?

Changes in forest composition or regional boundaries induced by rapid climatic change would magnify the complexity of National forest policy even further. Lands in forests now would require review relative to such competing needs as agriculture and residential use (which would also be adjusting to climatic change).

How Much Should Be Withdrawn From Timber Production?

Where the productivity of wood is significantly reduced, increased, or shifted, a policy question that would surely arise concerns whether forest lands should be reallocated to maintain timber production. If so, how should competing forest uses, such as watersheds, parks, and wilderness, be treated? How much of each can the United States afford under changed climatic conditions? Should the Federal Government purchase more forest lands to support all public needs?

In the short term, forest managers could compensate for some loss of productivity by improved technology, though at increased costs. An example would be establishing more drought-tolerant plantations through genetic selections, improved nursery stock, and more intensive silvicultural practices (e.g., weed control and thinning). Introducing new species adapted to warmer climates might be possible in some locations, but this would call for developing new silvicultural regimes and use methods -- possible, but expensive in time and money. In the long term, if growing conditions become extremely difficult on some U.S. forest lands because of climatic changes, investment in tree crops at such locations could become unattractive altogether.

How Should We Manage Federal Forests?

The National forests under the USDA Forest Service are managed according to a series of complex legal directives and administrative procedures, beginning with the Organic Act of 1897 (Woodman). Ultimately, the objective became to manage the National forests for multiple uses, with timber on a sustained-yield basis and certain lands set aside as wilderness areas. The National Forest Management Act of the mid-1970s requires 15-year management plans for each National forest subject to public review.

Lands managed by the Department of Interior are under similar mandates. For example, a congressional act passed in 1976 charged the Bureau of Land Management to manage its 2.3 million ha of forest and range land according to multiple-use and sustained-yield principles. Similarly, the National Park Service is mandated to manage National parks, monuments, historic sites, and so forth, for the recreational enjoyment of people. Such activities as timber harvesting, hunting, mining, and grazing are not permitted. In addition to the Federal Government, most States, many counties, and some municipalities own forest lands.

The Forest and Rangeland Renewable Resources Planning Act of 1974 requires the Secretary of Agriculture to make periodic reviews of the nation's forest and rangeland resources. The act was amended in 1976 to also require management plans for the National forests. In the future, these assessments and planning efforts should include consideration of the possible effects of predicted climatic changes. One key issue is the level of priority given to maintaining forest health under changed climatic conditions. For instance, under more adverse environments, should National forests be left to decline as a natural process, thereby losing esthetic values in parks, water yields from watersheds, and highly productive timber crops? Or should silvicultural forest techniques, such as thinning, weed control, and fertilization, be employed to "save" them? This question and others will challenge the fundamental concepts of the benefits of multiple use and sustained yield of forests.

How Can We Ensure National Goals?

At the minimum, Federal agencies must plan and act in concert with the State forest organizations. In the first half of this century, the Federal Government attempted to regulate forest harvests on Federal and private lands. Development of this policy did not survive strong public concern and intense political debate against such policy (Worrell, 1970); the same sentiment would likely exist today and in the near term. However, under the influence of rapid climatic change, the nation may once again have to face the touchy issue of what restraints or forest practices must be regulated for all public and private lands.

Solomon and West (1985) point out that while climatic change might disrupt forest ecosystems in the future, it is uncertain whether forest managers could or would be able to apply silvicultural practices on a scale large enough to maintain the net productivity of commercial forest lands in the United States. Some States (e.g., Washington, Oregon, and California) have laws specifying fire protection requirements, control burn practices, and reforestation minimums following timber harvests. Zoning, permits, licenses, and various taxation measures also have been attempted with mixed results. It is much easier to prevent owners from destroying forests than to compel them to implement silvicultural practices.

To keep pace with the rapid climatic changes projected, the U.S. reforestation effort conceivably would need to be doubled or tripled in size. In recent years, about 800,000 ha (2 million acres)/year (approximately 700+ million seedlings) have been reforested in the United States (USDA, 1982). Costs range from $200 to $700 per ha ($80 to $280 per acre) depending upon species, site preparation, plantation density, and planting method. Using $500 per ha ($200 per acre) as a mode, the total annual expenditure is near $400 million. About 0.4% of the commercial land base is reforested annually. At this rate, it would take 100 years to reforest 40% of the U.S. forest lands, assuming no repeat hectares to cover failures or harvests of the first plantations.

An expansion on the scale suggested above would require large investments in seed procurement, tissue culture capability, nursery capacity, and research to improve knowledge about the establishment and silviculture of drought-resistant plantations. Even if the dollar commitments were made, reforestation at this scale might only be possible if all forest lands were managed by one organization. The complex forest ownership pattern in the United States, therefore, would be an issue to overcome in a national reforestation program.

Who Should Pay?

Adjusting forest policies to address the issues arising from climatic change will most likely raise the costs of using the nation's forests -- whether for water, recreation, aesthetics, or timber. Additional research to answer many new questions will also require more funds. A major question will concern who should pay for these costs. Land owners? Forest users? Consumers? All taxpayers? The answers will come when better information is available on resulting forest effects, followed by public debate establishing new priorities for forest use in a changed climate.

RESEARCH NEEDS

The forest effects resulting from rapid climatic change are at present hypothetical. The change has not yet occurred, and many uncertainties are associated with the predictions. Effective policies to deal with new forest effects will require more information and fewer uncertainties that must come through forest ecosystem research. Four broad questions concerning U.S. forests frame the research needs for the 1990s: What will the effects be? How can they be measured reliably? How should they be managed? How can we ensure that research will be conducted in a timely fashion?

Effects

What will be the effect on the nation's forest ecosystems if climatic changes occur as predicted by the middle of the 21st century? While subsets of this question must include extent, magnitude, and risk considerations, additional knowledge is needed concerning the following factors:

1. Forest migration processes and rates, including the landscape processes that control the horizontal movements of forest, animals, and disturbances;
2. Interactions among the different landscape components and land-use practices that affect biodiversity, and water quantity and quality;
3. The impact of climate change alone and in combination with other natural or anthropogenic influences, such as insects, pathogens, CO_2 enhancement, air pollutants, UV-B radiation, and acid deposition on U.S. forests; and
4. The processes and mechanisms that play key roles in forest ecosystem effects -- both biologically as in photosynthesis and respiration, and physically as in flows of energy, carbon, water, and nutrients through ecosystems.

Methods

How can forest ecosystems be measured to reliably detect the effects of rapid climate change? Today, the response of ecosystems to environmental change is largely based upon extrapolating from field observations, from knowledge about seedlings or individual trees of a small number of commercially valuable species, and from computer models. The following must be accomplished:

1. A determination of the most useful integrating variables for forest ecosystems that indicate the effects of climatic change;
2. Effective sampling designs developed for experiments and long-term monitoring at the forest ecosystem scale; and
3. Improved models capable of projecting regional effects on forests across multiple spatial and temporal scales.

Management

What options are available to the public and private forest managers and owners in the United States to deal with the changes in the nation's forests that might occur in the next century? Research is needed to accomplish the following:

1. Understand the socioeconomic impacts of all forest ecosystem effects to clarify economic risks and alternatives; and
2. Develop technology to mitigate the adverse effects or to exploit the benefits of forest change, such as breeding, bioengineering, transplanting, fertilization, irrigation, and other management approaches.

Timing

The timing of the research is critical. The effects of climatic change may be some decades away, but this should not lessen the urgency to begin research toward better information and methods. The complexities of the science are very large. To build the required base of knowledge to deal with potential forest changes before they are upon the nation will require significant time and resources.

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DRAFT

CHAPTER 12

BIOLOGICAL DIVERSITY

FINDINGS

Unlike most other impacts, a loss of species and reduced biological diversity is irreversible. The ability of a natural community to adapt to changing climatic conditions will depend on the rate of climate change, the size of species ranges, the dispersal rates of the individual species, and whether or not barriers to species migration are present. Under rapid climate change, many species would be lost.

Species Diversity

- The effect of climate change on species and ecosystems will vary, with some species benefiting and others facing extinction. The uncertainties surrounding the rate of warming, individual species response, and interspecies dynamics, make impacts difficult to assess. However, climate change will alter competitive outcomes and destabilize natural ecosystems in unpredictable ways.
- In many cases, the indirect effects of climate change on a population, such as changes in habitat, in food availability, and in predator/prey relationships may have a greater impact than the direct physiological effects of climate change.
- Natural and manmade barriers to species migration, including roads, cities, mountains, bodies of water, agricultural land, unsuitable soil types, and habitat fragmentation, may exacerbate loss of species.
- The areas within the United States that appear to be most sensitive to changes in climate are those that have a number of threatened and endangered species, species sensitive to heat or drought stress, and species inhabiting coastal areas.

Marine

- The loss of coastal wetlands and coastal habitat resulting from sea-level rise and saltwater intrusion may profoundly affect the populations of all inhabitants of these ecosystems, including mollusks, shellfish, finfish, and waterfowl. However, there is no evidence to indicate these species would become extinct.

Freshwater

- Freshwater fish in large bodies of water, such as the Great Lakes, may increase in productivity, but some significant species could decline. Fish in smaller bodies of water may be more constrained in their ability to respond to climate change. They also may be adversely affected by reductions in water quality.

Migratory Birds

- Migratory birds are likely to experience mixed effects from climate change, with some arctic nesting herbivores benefiting and continental nesters and shorebirds suffering. The loss of wintering grounds due to sea level rise and changing climate could harm many species, as would the loss of inland prairie potholes due to potentially increased continental dryness.

Policy Implications

- Existing refuges, sited to protect a species or ecosystem under current climate, may not be properly located for this purpose under future conditions, or as species migrate.

- Wildlife agencies such as the Department of Interior, state government agencies and conservation organizations may wish to assess the feasibility of establishing migratory corridors to facilitate species migration.

- Areas that will become suitable future habitat for threatened and endangered species need to be identified and protected, such as lowland areas adjacent to current wetlands.

- The practice of restoration ecology will need to be broadened to restore ecosystems in new areas as climates shift.

- The increase in the number of species at risk as a result of climate change may require new strategies. Agencies such as the Fish and Wildlife Service's Endangered Species Program may wish to assess the relative risk of climate change and more current stresses on ecological systems.

- The museums and systematic collections of biological material in the United States may need to be mobilized to provide a comprehensive ability to describe the existing species of plants and animals and their ranges.

VALUE OF BIOLOGICAL DIVERSITY

Maintaining the biological diversity of our natural resources is an important goal for the nation. The preamble to the Endangered Species Act of 1973 formalizes this belief, stating that endangered and threatened species of fish, wildlife and plants "are of aesthetic, ecological, educational, historical, recreational and scientific value to the Nation and its people." We depend upon these biological resources for food, medicine, energy, shelter, and other important products. Reduced biological diversity could have serious implications for man, as untapped resources for research in agriculture, medicine, and industry are irretrievable lost.

The National Resource

Public and private lands in the United States provide sanctuary for an abundant diversity of plants and animals. About 650 species of birds reside in or pass through the United States annually. Over 400 species of mammals, 460 reptiles, 660 freshwater fishes, and tens of thousands of invertebrates can be found in this country, in addition to some 22,000 plants (U.S. Fish and Wildlife Service, 1981). These species compose a wide variety of ecosystem types within the United States, including coniferous and broad-leaf forest, grassland, desert, freshwater, marine, estuarine, inland wetland, and agricultural. Figure 12-1 shows the major ranges of natural vegetation in the United States.

The U.S. National parks, forests, wilderness areas, and fish and wildlife refuges are among the public lands that provide sanctuary for wildlife resources, including many endangered species. U.S. public lands, which encompass over 700 million acres (about 32% of the land area of the United States), support about 700 rare species and communities (Roush, 1986). Over 45% of the lands held by the Forest Service, Fish and Wildlife Service, NationalPark Service, and Bureau of Land Management are in Alaska, and over 48% are located in the 11 most western States (U.S. Department of the Interior, 1987). However, much of the nation's biological diversity lies outside these areas.

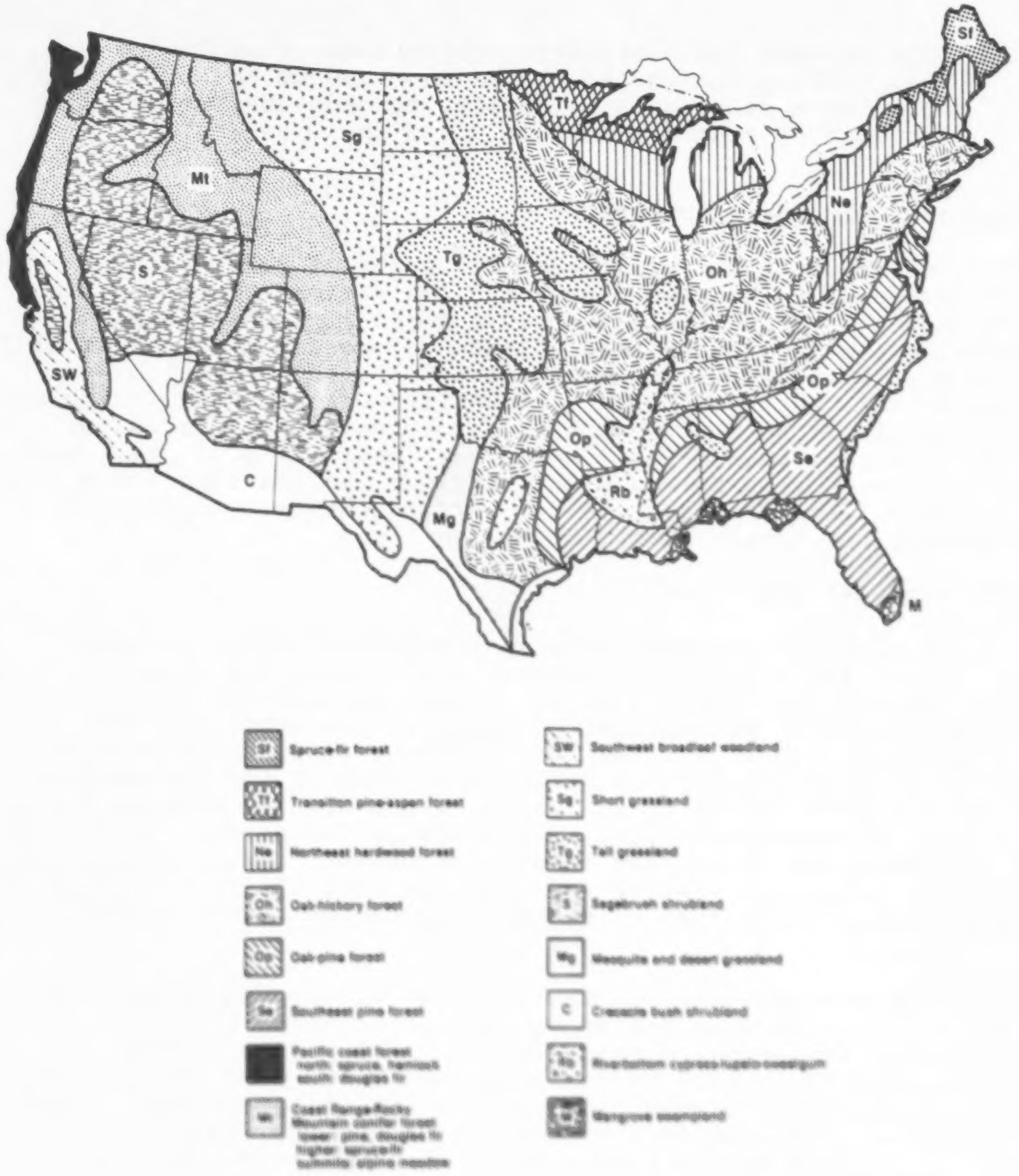
Sf
Tf
Sg
Mt
Ne
Tg
Oh
S
SW
Op
Se
C
Mg
Rb
M
Sf Spruce-fir forest
Tf Transition pine-aspen forest
Ne Northeast hardwood forest
Oh Oak-hickory forest
Op Oak-pine forest
Se Southeast pine forest
Pacific coast forest north: spruce, hemlock south: douglas fir
Mt Coast Range-Rocky Mountain conifer forest lower: pine, douglas fir higher: spruce-fir summits: alpine meadow
SW Southwest broadleaf woodland
Sg Short grassland
Tg Tall grassland
S Sagebrush shrubland
Mg Mesquite and desert grassland
C Creosote bush shrubland
Rb Riverbottom cypress-tupelo-sweetgum
M Mangrove swampland

Figure 12-1.   Natural vegetation in the United States.

Source: Hunt, 1972.

Private land holdings also account for a great deal of this nation's biological endowment. Private groups, such as the Nature Conservancy and the Audubon Society, manage 500,000 acres and 86,000 acres, respectively, for biological diversity.

GENERAL COMPONENTS OF BIOLOGICAL DIVERSITY

Biological diversity can be broadly defined as the full range of variety and variability within and among living organisms. It includes species diversity, genetic diversity, and ecosystem or community diversity.

Species Diversity

Each species occurs in a characteristic range or geographical area. The factors controlling species ranges are critical constraints on biological diversity. The presence of a species in an area suggests that the species must have successfully achieved the following: (1) dispersed into an area (no barriers to dispersal such as bodies of water or unsuitable soil types were present); (2) survived in that area (the physical characteristics of the area were suited to the animal's physiology, and food was available); and (3) became established in the area (the organism found an appropriate place in the food web in the absence of excessive competition and predation, and was able to reproduce).

The stresses brought about by development, overuse, and alteration of habitat have fragmented much of the world's natural habitat and have created many new barriers; consequently, for many species, dispersal has become much more difficult than it was in the past. For other species, man has inadvertently aided dispersal and has caused rapid spread in recent years. Such practices as clearcut logging prevent the dispersal of species adapted to dense forest conditions (e.g., flying squirrels) and promote the dispersal of species suited to open areas (e.g., deer).

Currently, 495 species are listed as endangered within the United States, and over 2,500 species await consideration for that status by the Fish and Wildlife Service. The list of endangered species is dominated by plants, birds, fishes, and mammals but also includes insects, amphibians, reptiles, mollusks, and crustaceans (U.S. Fish and Wildlife Service, 1988).

New species are created through the evolutionary process of speciation and are lost through extinction. Speciation generally requires a period of time considerably greater than centuries. However, extinction as a result of human activities is occurring extremely rapidly and at an increasing rate. Owing to its slowness, the process of speciation does little to offset species loss to extinction.

It is difficult to determine the exact rate of species extinction because the number of species on the Earth is known only to an order of magnitude. A recent estimate by Wilson (1988) places the total number of species between 5 and 30 million. Assuming 10 million species, Wilson made the rough calculation that one in every 1,000 species is lost each year. Wilson then compared this to estimates of extinction rates over geologic time, which ranged between 1 in every 1 million and 1 in every 10 million per year.

Species diversity is fundamental to an ecosystem's function and integrity. The significance of rare species should not be underestimated. A narrowly or sparsely distributed species may be a keystone in an ecosystem, controlling the structure and functioning of the community, or it may be a species of great and yet unknown value to humans.

Genetic Diversity

Each species that persists has a characteristic genetic diversity. That is, the individuals of that species have among them a collection of genes and gene combinations that may be more or less diverse.

The pool of genetic diversity within a species constitutes an adaptation to its present environment as well as a store of adaptive options for a new or changed environment. The loss of genetic diversity can contribute to the extinction of a species by reducing its ability to adapt to changing environmental conditions.

Generally, species with larger populations have greater genetic diversity. Species that are divided into partly connected subpopulations also tend to have greater genetic diversity. Species near extinction represented by few individuals in few populations have lower genetic diversity, a situation exacerbated by inbreeding.

Community and Ecosystem Diversity

Overall species diversity is also a function of the number of different types of areas in which communities can be built.* Ecosystem diversity refers to the distinctive assemblages of species and biotic processes that occur in different physical settings around the world.

FACTORS AFFECTING THE RESPONSE OF BIOLOGICAL DIVERSITY TO CLIMATE CHANGE

Natural communities are a significant indicator of climate change. Historically, biological communities have responded to changes in climate through large-scale geographic shifts, changes in species composition, physiological adaptation, and extinction (Peters and Darling, 1985). Local climate appears to be the primary factor defining an environmental setting and determining the species composition and spatial patterns of communities in terrestrial zones (Bolin, 1986). Temperature means, temperature extremes, and precipitation are the factors most often affecting the natural distributional limits of a species (Ford, 1982), while the actual distribution of a species is also affected by soil type, soil moisture, ecological dynamics, and regional isolation.

Rate of Climate Change

Predicting how a species or ecosystem might respond to a given environmental change is difficult. Adaptation to climate change will inextricably depend on the rate of climate change. For some species, migration rates may be inadequate to keep up.

The infinite number of combinations of dispersal range and reproductive age make the potential rate of migration different for every species. Paleorecords suggest migration rates between 10 and 20 km per century for chestnut, maple, and balsam fir, and between 30 and 40 km per century for some oak and pine species (see Forestry chapter in this report). On the other hand, cattle egrets have shown a much quicker migration rate by colonizing all of the North American tropics within approximately 40 years.

As species shift at different rates in response to climate change, communities may disassociate into new arrangements of species. Local extinction can result either directly from physiological pressures or indirectly from changes in interspecies dynamics. Hence, the affect of climate change on an area will be to cause sorting and separation of species owing to the differential rate of migration and species retreat (Ford, 1982). Ecosystems, therefore, will not migrate as a unit.

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*The new discipline of landscape ecology attempts to relate topographic diversity to community and species diversity.

The rate of climate change will be crucial to the survival of the species. A 3°C increase in temperature, for example, would effect a several hundred kilometer poleward shift in the temperate vegetation belts (Frye, 1983). If this change took place within a century, species would need to migrate several kilometers each year to adapt to this warming. Plants have a wide range of migration rates, and only some may be able to achieve this rate.

Many factors make evaluating the impact of climate change on ecosystems difficult. The great interdependencies among species in an ecosystem add considerable uncertainty to the effect that the various responses of individual species will have on the system. An impact upon a single species could significantly change the entire ecosystem. For example, elimination of a tree species in a region could have a significant effect on the whole forest ecosystem including birds, insects, and mammals.

Animal populations are generally much more mobile than plants. But animal distributions heavily depend on vegetation for food, protection, and nesting habitat. Species not directly dependent on vegetation ultimately depend on some other species that is. The ranges of the fig wasp and the fig depend entirely upon one another. In this case, the plant species depends on a single pollinator, and the insect species relies upon a single species of plant for food (Kiester et al., 1984).

Species do not immediately respond to changed and changing environmental conditions. A negative response, such as local extinction in an area, is usually quicker than the positive response of new species' colonization of a region (see Forestry chapter of this report). In the Arctic, the lag period between climate change and species response (colonization) may be several hundred years (Edlund, 1986). This lag period will leave areas open for weedy, opportunistic species that can quickly migrate and propagate in a region.

Barriers to Response

How quickly species migrate is affected by natural and manmade barriers and by competition. Peters and Darling (1985) examined potential species' responses to climate change, ecological interactions, and barriers to adaptation. Physical barriers include mountains, bodies of water, roads, cities, agricultural land, inappropriate soil type, and habitat heterogeneity (landscape patchiness).

Reserve and Island Species

Species living on reserves have additional constraints on their ability to respond to climate change that are similar to those of island species. This problem has become known as the island dilemma. Species on reserves are often remnants of larger populations and are more susceptible to environmental stress. Additionally, reserves that originally may have been well sited to protect a vulnerable population and its habitat may, after climate change and population response, exist outside the now suitable range. Figure 12-2 illustrates this problem.

Species on reserves are likely to be pressured from two directions as a result of climate change. A population isolated on a reserve surrounded by altered or unsuitable habitat receives little immigration from populations outside the reserve. Also, that population may not be able to colonize areas outside the reserve as these areas become suitable because of development or other alterations of habitat. Large reserves and buffer zones around reserves help to lessen this problem. Corridors between reserves lessen the problem of spatial isolation by allowing for some migration between reserves.

Habitat Area

Even without the added pressure of climate change, reserve populations are stressed because many reserves are not large enough to support a self-sustaining population (Lovejoy, 1979). The predictive theory of island biogeography (MacArthur and Wilson, 1967) showed that, other factors being equal, large islands accommodate larger numbers of land-dwelling species than do small islands. This held true for other ecologically isolated islands, such as mountaintops, woodlots, and lakes. Also, when large ecosystems become smaller through fragmentation, the number of species always declines. Figure 12-3 shows how mammalian extinctions have been inversely related to refuge area in North American parks.

Mountain Species

Just as species can migrate latitudinally, they can respond altitudinally to climate change by moving up a mountain slope.

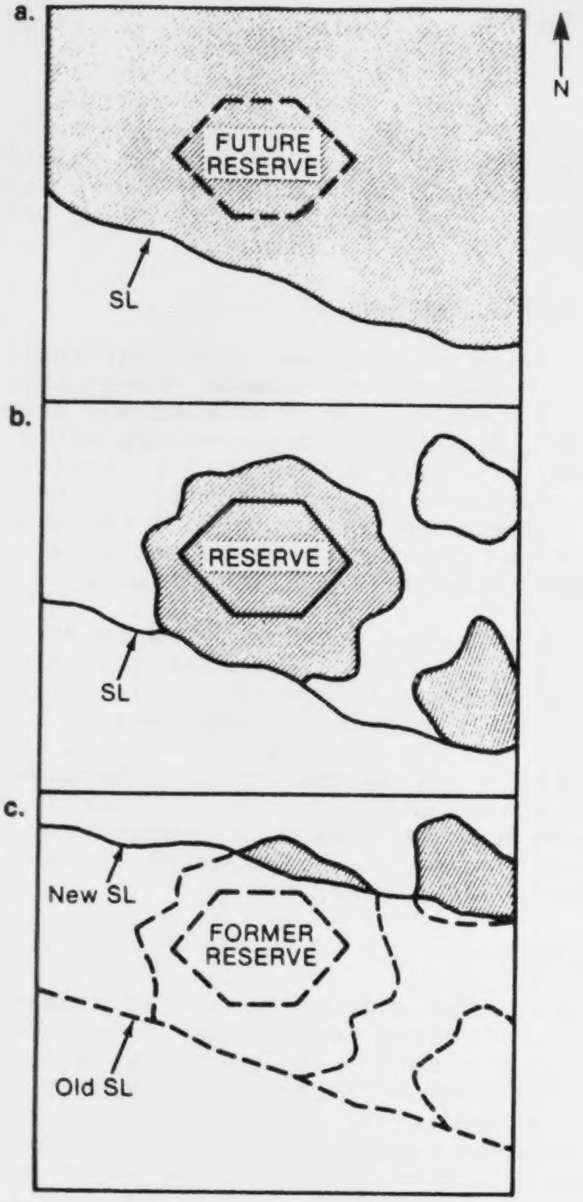
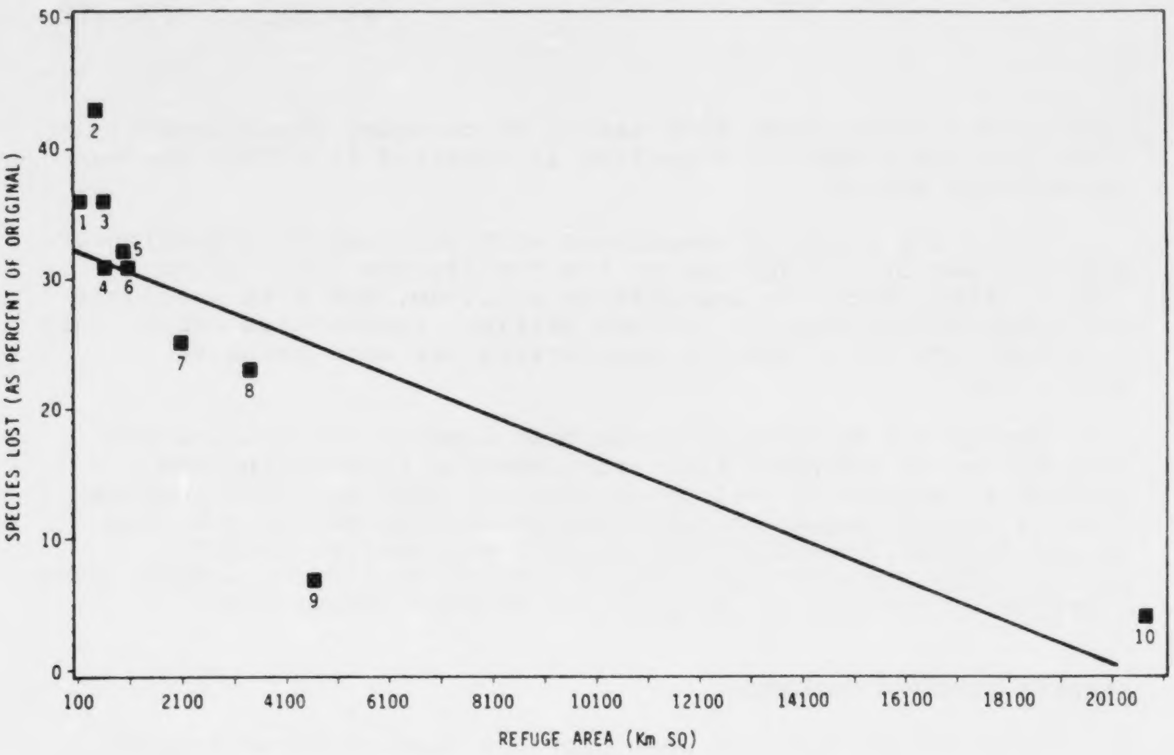

a.
N
FUTURE RESERVE
SL
b.
RESERVE
SL
c.
New SL
FORMER RESERVE
Old SL

Figure 12-2. Effect of climate chante on biological reserves. Hatching indicates the following: (a) species distribution before human habitation (SL indicates southern limit of species range); (b) fragmented species distribution after human habitation; (c) species distribution after warming.

Source: Peters and Darling (1985).



PARK		AREA (km^2)	PERCENT OF ORIGINAL SPECIES LOST
1)	Bryce Canyon	144	36
2)	Lassen Volcano	426	43
3)	Zion	588	36
4)	Crater Lake	641	31
5)	Mount Rainier	976	32
6)	Rocky Mountain	1,049	31
7)	Yosemite	2,083	25
8)	Sequoia-Kings Canyon	3,389	23
9)	Glacier-Waterton	4,627	7
10)	Grand Teton-Yellowstone	20,736	4

Figure 12-3. Habitat area and loss of large animal species in North American parks (1986)

Source: Newmark (1987).

Species can often adapt more easily to changing conditions on a slope because a shorter migration is required to effect the same temperature change.

Among the problems associated with altitudinal migration are displacement of the species at the top (Peters and Darling, 1985). Also, with the increase in altitude, the area available for colonization usually becomes smaller, communities become very isolated, and these smaller populations are more prone to extinction.

Peters and Darling conclude that some of the species and communities at greatest risk from changing climate include peripheral populations (located near the edge of a contracting species range); geographically localized species (reserve and island species); genetically impoverished species (small populations); specialized species (living in narrow niches); poor dispersers; and alpine, arctic, and coastal communities.

CLIMATE EFFECTS RESEARCH

This section reviews some previous studies of ecological response to past changes in climate, recent studies of potential response to anticipated future climate change, and studies funded by EPA for this report, which use climate change scenarios from general circulation models for a doubled CO_2 environment (see Table 12-1).

In only the last few years, biological diversity has emerged as both a major scientific and policy issue. At present, much effort is being devoted to both the scientific and policy aspects of biological diversity. This effort should result in much new information is the relatively near future.

Forest Ecosystems

The tree species that make up any forest are major factors in determining the biological diversity found there. Treesprovide a multitude of habitats and are the basis of much of the food web in a forest.

The changes in forest composition resulting from climate change, (see Forests: Chapter 11), will have significant implications for biological diversity. Potential northerly range shifts of several hundred to a thousand kilometers may be limited by the tree species' ability to disperse. One possibility is that southern pine forests will move farther north into the

Table 12-1. Studies Conducted for This Report.
Cited in this Chapter

- Potential Responses of Great Lakes Fishes and Their Habitat to Global Climate Warming -- Magnuson, Regier, Shuter, Hill, Holmer and Meisner, University of Wisconsin
- The Effects of Global Climate Change on the Water Quality of Mountain Lakes and Streams -- Byron, Jassby and Goldman, University fo California at Davis
- The Effects of Climate Warming on Lake Erie Water Quality -- Blumberg and DiToro, HydroQual, Inc.
- Ecological Effect of Global Climate Change: Wetland Resources of San Francisco Bay -- Josselyn and Callaway, San Francisco State University
- Projected Changes in Estuarine Conditions Based on Models of Long-Term Atmospheric Alteration -- Livingston, Florida State University

regions currently occupied by mixed hardwood species. Some of these hardwood forests contain the highest tree species diversityfound anywhere in the United States (Braun, 1950). As they migrate north, species would inevitably be lost, and overall biological diversity would substantially decrease.

As forests are disrupted, the land will be invaded by weedy, opportunistic species, creating a system with very low diversity similar to that following logging. Ultimately these systems will not persist as succession takes place, but the pattern of succession following the removal of a forest by rapid climate change is unknown.

Tropical Forest Ecosystems

The greatest concentration of biological diversity in the world is in the rain forests of the Tropics (Wilson, 1988). Besides reducing diversity, deforestation contributes to disrupting the global carbon cycle by releasing CO_2 into the atmosphere and will directly affect the rate of climate change (Prance, 1986). Indeed, on a global scale the problems of tropical deforestation, rapid climate change through (among other factors) increased CO_2 production, and the loss of biological diversity can be seen as aspects of the same problem.

Tropical forests are also important as wintering grounds for migratory birds coming from the United States and as sources of new knowledge, because the patterns of interactions between species and climate are at their most sensitive and complex there. The Tropics may provide important leading indicators of climate change (Robinson, 1978; Janzen, 1986).

Freshwater Ecosystems

A study conducted by Magnuson et al. concludes that in most areas of the Great Lakes, climate warming would increase the amount of optimal thermal habitat for warm-, cool-, and cold-water fishes (see Chapter 5, Great Lakes); although overall productivity would increase, overall biological diversity could decrease through intensified species interactions.

A study by Byron et al. on mountain lakes suggests that climate change would cause a range of impacts, including higher productivity, changes in species composition, and decreased water quality resulting from an increase in algal growth (see Chapter 4, California). Blumberg (see Chapter 5, Great Lakes) found that thermal stratification in Lake Erie could decrease dissolved oxygen levels. This result, with possible loss of biological diversity, is likely to be repeated in many lakes.

The combined pressures of warmer waters, saltwater intrusion, and a rising sea level will significantly affect estuaries. The regional studies suggest that coastal estuaries are likely to see a growth in marine species and a loss of some estuarine species. A study by Josselyn on the San Francisco Bay estuary suggests a decline in species that use the delta for spawning (see Chapter 4, California). Livingston concluded that crabs, shrimp, oysters, and flounder in the Apalachicola estuary could not survive the warming projected by the GISS and GFDL scenarios (see Chapter 6, Southeast).

Saltwater Ecosystems

In general, a warmer global climate is expected to increase productivity in ocean fisheries, but the location and relative abundance of species are likely to change (Sibley and Strickland, 1985). Up to some threshold temperatures, such as 2°C, warmer ocean temperatures are likely to increase ocean productivity, but beyond that threshold, productivity could decline (Glantz, 1988). It is likely that as productivity decreases, biological diversity would decrease as well.

Coral Reef Ecosystems

Coral reefs provide the structural base for the very biologically diverse reef ecosystems. Coral reefs in the Caribbean and the Pacific may be severely stressed as a result of warmer water temperatures and the rising sea level associated with climate change. Extensive bleaching of coral (the expelling of symbiotic brown algae in response to environmental stress) occurred in the Pacific after the 1982-83 El Nino (Glynn, 1984) and in the Caribbean following a summer of elevated water temperatures in 1987 (Roberts, 1987). Loss of the brown algae, the primary food source of the coral, is thought to kill coral, making the reef ecosystem vulnerable to erosion and physical devastation.

Coral reefs also will be affected by sea level rise. Studies by Buddemeier and Smith (1987) and Cubit (1985) suggest that vertical accretion of reef flats eventually may be unable to keep up with an accelerating rise in sea level. Reef flats also may be subject to the stress of increasingly large waves, erosion, and sedimentation, which can inhibit coral growth (Buddemeier, 1988).

Arctic Ecosystems

Within the North American arctic, plant size, vigor, and reproduction could be expected to increase with higher temperatures. Some low-lying plants would most likely become upright, and there would be a northerly movement of the tree line and all vegetative zones (Edlund, 1986).

However, in the Arctic, rising temperatures may be a mixed blessing. Overall biological productivity is likely to increase, and some species may be able to increase their range. But many species specially adapted to the Arctic will face the same type of problem that mountaintop species face: they will have nowhere to go once they reach the Arctic Ocean. Thus, native Arctic species may be specially at risk. Other Arctic species may face their own problems. For example, caribou will be severely harmed if rivers do not freeze for long enough periods to allow for migration.

Migratory Birds

Migratory waterfowl are likely to experience very mixed effects as a result of warmer temperatures (Boyd, 1988). Herbivorous, Arctic nesting species, such as geese, are likely to benefit from the shortened winter season and from the increases in vegetation, in nesting habitat, and in ecosystem productivity (Harington, 1987). Smaller Arctic nesting shorebirds, on the other hand, are likely to be harmed by the encroachment of taller vegetation, potentially eliminating the preferred low-lying tundra breeding ground. Other effects on shorebirds could result from changes in ecosystem predator/competitor relationships and changes in the seasonal timing of such events as larval blooms, upon which these birds depend for nourishment while in a flightless stage and during migration (Myers, 1988).

Waterfowl that breed in the continental interior may suffer more than arctic nesters. Over half of all waterfowl in North America originate in the prairie pothole region, a large agricultural area riddled with highly ecologically productive permanent and semipermanent wetlands. Increased temperature and changes in seasonal precipitation could reduce the highly variable number of potholes (wetlands) in the area and could significantly impair the productivity of breeding ducks (Burke, 1988). Over 35% of the seasonal wetlands within the prairie pothole region were dry during the breeding season owing to the drought of 1988 (U.S. Fish and Wildlife Service, 1988). The Fish and Wildlife Service is forecasting that only 66 million ducks will migrate during the fall of 1988, a total of 8 million fewer than in 1987 and the second-lowest on record (Irion, 1988). The productivity index for mallards (number of young per adult) is 0.8, which is down by over 20% from the historical average (U.S. Fish and Wildlife Service, 1988).

Waterfowl and other migratory birds are likely to be affected on both ends of their migratory journey and at staging areas along the way. The loss of coastal wetlands, already an area of great concern in the United States, reduces the amount of habitat available to waterfowl, creating population pressures on a limited resource. Of the 215 million acres of wetlands in the coterminous United States at the time of settlement, fewer than 99 million acres (46%) remain (U.S. Fish and Wildlife Service, 1987). Loss of an additional 26-82% of existing coastal wetlands is expected over the next century as a result of a 1-meter rise in sea level, saltwater intrusion, and human development (see Sea Level Rise: Chapter 9). Loss of wintering habitat along the Gulf of Mexico would affect many waterfowl, including mallards, pintails, and snow geese.

The Tropics, which may be significantly altered by rapid climate change, is the winter home for many species of migratory birds. The need to protect a species in all parts of its range underscores the truly global nature of the effects of rapid climate change on biological diversity (Terborgh, 1974).

Endangered Species

Hundreds of species are currently listed as endangered in the United States, and several thousand await consideration for that status. These species are likely to be stressed further as a result of climate change.

Threatened and endangered species of the Southeast are very susceptible to the impacts of sea level rise. Some species potentially at risk in that region include the Key deer, manatee, Florida panther, and Everglades kite (Breckenridge, 1988). Climate change could also greatly increase the number of rare, threatened, and endangered species in the United States.

Other Direct and Indirect Stresses

As plant and animal species experience increasing pressures from changes in temperature, precipitation, and soil moisture, so too will agriculture and urban water supplies. The changes that result from the human response to climate change may have the greatest impact on biological diversity. If the continental interior of North America dries, for example, habitats may be cultivated, and our current uses of water resources may change. These secondary effects may also prove detrimental to biological diversity.

NATIONAL POLICY IMPLICATIONS

Climate change presents new challenges for policymakers, regulators, and resource managers. Planning for climate change may help to minimize the disruption to natural systems and facilitate adaptation under changing conditions. Decisions will need to be made in an environment of increased pressure on many other resources.

Policies regarding rare and endangered species are likely to change as the number of species at risk greatly increases. As more species become stressed and potentially threatened by climate change, reevaluation of protection policies may be required. The tradeoffs between protection of individual species and species' habitat and the broader protection of biodiversity will have to be reexamined. As a part of this question, decisions concerning whether to protect existing communities or foster the establishment of new ones will need to be made.

Management Options to Maintain Biological Diversity

Only a limited number of techniques are available for maintaining biological diversity. However, these techniques can be adapted and intensified to meet the potentially great impacts of rapid climate change.

Maintenance of Native Habitats

The most direct way to maintain biological diversity is to manage land to retain ecosystems, communities, and habitats. This has been successfully undertaken on a broad scale by Federal and State governments and by private organizations. Ecosystem conservation, especially as represented by the National Parks and other large reserves, maintains much of our national biological diversity. This will continue to be a useful first step for maintaining biological diversity in the face of climate change.

Land acquisition and management policies will need to take climate change into account. Climate change and the future requirements of whole ecosystems must be considered in siting and managing reserves. To preserve functioning ecosystems, large areas of land will be required. Preserves need to be at least large enough to support self-sustaining populations. Lands that will be more important as future plant and animal habitat need to be identified, evaluated, and set aside. Although identification of appropriate future habitat is difficult, and highly dependent on the future rate and extent of climate change, some areas, such as lowland areas adjacent to current wetlands, hold good potential for habitat protection.

To protect a species, alternative sites should be considered with regard to the ecological needs of target species under changing conditions. Siting preserves in mountainous areas is beneficial because it allows for the shorter-distance altitudinal shifts of adjustment to changing climate. Stream corridors, which can be effective avenues of dispersal for terrestrial as well as aquatic organisms, should be protected wherever possible. Providing corridors for migration between reserves also will enhance the ability of wildlife to adapt to climate change. Ideally, these corridors should be wide enough to maintain the ecosystem characteristics of the reserve in their center. Some species do not find the habitat conditions of narrow corridors suitable for migration.

Maintenance of Species in Artificial Conditions

When individual species are threatened with extinction, a possible option is to ensure that the species is propagated in captivity. Indeed, some rare species, such as the Pere David deer and the California condor, now exist only in captivity. This technique can be made to work for a variety of species, depending on their biology and the degree to which they successfully adapt to captive conditions. As more species become threatened with extinction due to climate change, the effort applied in this area may have to increase dramatically. However, only a tiny fraction of the nation's species can be maintained in this way.

Restoration of Habitat

Restoration ecology is a new discipline whose goal is to develop methods to restore damaged ecological communities to their prior unaltered state. Except in forestry, where reforestation has a longer tradition, restoration ecology has been in existence for only a few years. Nonetheless, it offers some real promise for ameliorating the effects of rapid climate change.

Normally, restoration is done at the site where the community previously existed and was altered or damaged. Historical and baseline information is used to manage the species in such a way as to eliminate unwanted new species and to encourage and possibly reintroduce native species.

The next step in restoration ecology is to restore natural communities on sites where they have not previously existed. This activity has not yet been attempted but may be necessary to save communities displaced by climate change. If the climate changes so that many of the key species of a community can no longer survive in their original range, and if the species are incapable of dispersing and establishing themselves elsewhere, then the artificial transplantation of entire communities may become necessary. This transplantation of communities would be a monumental task and could help to save much biological diversity, but it cannot possibly be undertaken on the scale necessary to preserve all species threatened by climate change. Restoration ecology can be useful for extending reserve boundaries and providing migratory corridors.

Planning Options

While there are only a few management techniques to maintain biological diversity, many different groups in our society can implement them. These groups can be divided into the private and public sectors.

Many different groups in the private sector, ranging from private individuals to large conservation organizations, will have an interest in maintaining biological diversity. However, all will need information about the current and probable future state of biological diversity. The Federal Government may be able to play a role here by providing information on the study of biological diversity.

Resource managers and policymakers should incorporate climate change into their long-term planning. Periodic reviews of the management plans for public lands should include consideration of the possible effect of climate change.

The four major Federal land management agencies develop plans intended to lay out a comprehensive framework and direction for managing Federal land. Land Resource Management Plans, required for each National forest, define the direction of management in the forest for the next 10 to 15 years. In addition, the Forest Service prepares 50-year plans, as required by the Resource Conservation Act. The National Park Service prepares a General Management Plan for each unit in the system that defines a strategy for achieving management objectives within a 10-year time frame. A Statement for Management is also prepared for each National park and is evaluated every 2 years; this includes a determination of information needs. The Bureau of Land Management's (BLM's) Resource Management Plans and the Fish and Wildlife Service's Refuge Master Plans are prepared and revised as needed for BLM Resource Areas and Wildlife Refuges (U.S. Department of the Interior, 1987).

The Federal Government manages an enormous amount of land and should consider management options to preserve biological diversity on much of that land. The major management techniques of habitat maintenance and restoration ecology could be applied by the agencies actively responsible for managing the nation's public lands.

RESEARCH AND DEVELOPMENT NEEDS

The ability to protect biological diversity is severely restricted by a lack of knowledge regarding the rate of climate change, the precise nature of the change, how individual species will respond, and how ecological balances will shift. Increased research effort is needed in three areas: identification of biological diversity, species interactions and biological diversity, and management options for biological diversity.

Identification of Biological Diversity

The first and most pressing need is for more and better coordinated research to simply identify the biologically diverse resources of our country. This involves both systematics (organism classification) and ecology. The nation needs a more coordinated ability to identify its plants and animals (see H.R. 4335), and it needs range maps and habitat requirement information for those species.

The apparently simple task of identifying the species of plants and animals that exist in a given area is actually a major barrier to further understanding. Common species are usually relatively easy to identify, but even they present serious problems when attempts are made to decide whether a widespread group is, for example, one or two species. The nation's museums and systematic collections needs to be mobilized to solve this problem. For example, there is currently no federally sponsored Flora (listing of all known plants) of the United States. In this regard, the United States lags behind many Third World countries, such as Panama and Peru.

Species Interactions and Biological Diversity

The second area needing research is the direct effects of climate on species and the indirect interactions of species with other species dependent on climate. Comprehensive mapping of species ranges along temperature and moisture gradients would provide valuable information. The direct effect of climate change on vegetation needs to be better assessed, and more estimates of species dispersal rates would significantly improve our ability to identify species at greatest risk.

A variety of ecosystems within a diversity of climatic regions and terrains need to be intensively studied using analogue climate regions under changed climate conditions. Although an ecosystem's response under changing climate conditions will not be wholly predictable, modeling individual ecosystem responses would enhance knowledge of the likely effects. Further research on how species interact and how trophic structures might change with climate would help predictive capabilities.

It will be impossible to study in detail even a fraction of the nation's species. Those groups chosen for study either must be representative of many species or must possess some special properties (such as extreme sensitivity to climate change). The method of deciding which group to study is itself a major outstanding research question.

Management Options for Biological Diversity

Management options are limited in both number and scope. Research is needed to increase the scope of the current management options and to discover new options.

National parks, forests, and wildlife refuges are suitable areas for study. In-depth evaluation of 5 to 10 of these areas could provide valuable information regarding the range of impacts and management options.

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DRAFT

CHAPTER 13

IMPACT OF CLIMATE CHANGE ON AIR QUALITY

FINDINGS

- Changes in regional temperatures, precipitation patterns, clouds, windspeed and direction, and atmospheric water vapor that will accompany global climate change will affect future air pollution levels and episodes in the United States.

- While uncertainties remain, it is likely that an increase in global temperatures will have the following effects on air quality, if other variables remain constant.

  - Ozone levels in many urban areas would increase because higher global temperatures would speed the reaction rates among chemical species in the atmosphere.

  - Manmade and natural emissions of hydrocarbons and manmade emissions of nitrogen and sulfur oxides would increase with a temperature rise. Natural emissions of sulfur would also change, but the direction is uncertain. The hydrocarbons and nitrogen oxides participate in reactions that produce ozone.

  - The formation of acidic materials (such as sulfates) would increase with warmer temperatures because sulfur and nitrogen oxides would oxidize more rapidly. The ultimate effect on acid deposition is difficult to assess because of changes in clouds, winds, and precipitation.

  - Visibility may decrease because of the increase in hydrocarbon emissions and in the rate at which sulfur dioxide is oxidized to sulfate.

- Preliminary analyses of 4°C temperature increase in the San Francisco Bay area suggest that maximum ozone concentrations would increase by approximately 20%, that the area in which the National Ambient Air Quality Standard (NAAQS) would be exceeded would almost double, and that the number of people-hours of exposure would triple. The Midwest and Southeast also would incur high concentrations and an increase in the area of high ozone by a factor of three.

- The additional costs for air pollution controls that would be caused by global warming cannot be estimated at this time. Increases in ambient ozone levels resulting from climate change could increase the number of nonattainment areas and make attainment more expensive in many regions. Preliminary estimates suggest that an expenditure of several million dollars per year may be necessary for additional volatile organic compound (VOC) controls.

- Because of the close relationship between air pollution policies and global climate change, it is appropriate for EPA to review the impact of global climate change on air policies and the impact of air pollution regulations on global climate change.

RELATIONSHIP BETWEEN CLIMATE AND AIR QUALITY

The summer of 1988 provided direct evidence regarding the importance of weather to pollution episodes in the United States. Despite significant progress in reducing emissions of many pollutants over the last decade, the extended stagnation periods and high temperatures caused ozone levels in 76 cities across the country to exceed the national standard by at least 25%. Whether this recent summer is an appropriate analogue for the future cannot be determined with certainty, but scientists have recognized for some time that air pollution does vary with seasons and is directly affected by ventilation, circulation, and precipitation, all of which could be affected by future global climate changes.

Ventilation

Two major factors, referred to as "ventilation" when considered together, control the dilution of pollutants by the atmosphere: windspeed and the depth of the atmospheric mixing layer (frequently called the mixing depth). If windspeed is high, more air is available to dilute pollutants, thus lowering pollutant concentrations. The mixing layer (the distance between the ground and the first upper-layer inversion) tends to trap pollutants because the inversion on top of it acts as a barrier to vertical pollutant movement. Thus, pollutant concentrations decrease as mixing depth increases, providing greater dilution.

The ventilation characteristics of an area change, depend on whether a high- or low-pressure system is present. Low-pressure systems usually produce good ventilation because they normally have greater mixing depths and windspeeds, and precipitation is often associated with them. High-pressure systems, on the other hand, generally produce poor ventilation conditions because they frequently have smaller mixing depths on their western sides and lower windspeeds. They also tend to move more slowly than lows, so more emissions can enter their circulation patterns. In addition, they are frequently free of clouds, resulting in maximum sunlight and therefore more photochemical ozone production during the day. Also, during the evenings, the clear skies allow surface-based (see below) inversion layers to form, concentrating pollutants in a small volume of air and often creating very high air pollution levels.

Climatologically, certain places in the country are frequently windy (Figure 13-1), and others frequently have large mixing depths (Figure 13-2). These areas will have cleaner-than-average air if they do not contain not too many pollutant sources. Areas frequently affected by high-pressure systems -- causing lower windspeeds and smaller mixing depths -- will have more major air pollution episodes.

Circulation

Two semipermanent high-pressure systems are important to the global circulation pattern and greatly influence U.S. air pollution climatology: the large Pacific high, which is often situated between the Hawaiian Islands and the west coast of North America, and the Bermuda high, located over the western Atlantic Ocean.

The Pacific high often results in extended periods of air stagnation over the western United States from Oregon and California to over the Rockies, and is responsible for many severe ozone episodes in southern California. Air stagnation associated with the westward extension of the Bermuda high occurs most often during the summer months and affects the eastern United States from southern Appalachia northward to New England; it is an important cause of the air stagnation that occurs in the heavily populated eastern part of the country. Within the Bermuda high, pollutants are slowly transported from the industrial areas of the Ohio River Valley into the populated areas of the Northeast. It is also responsible for the general southwest-to-northeast airflow in the summer, carrying pollutants along the metropolitan corridor from Richmond to Boston and exacerbating the ozone problem in the Northeast.

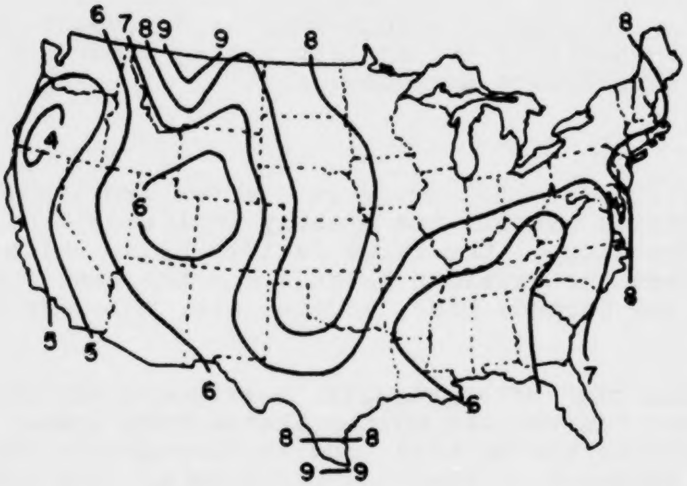
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Figure 13-1. Mean Annual Windspeed Averaged Through the Afternoon Mixing Layer (speeds are in meters per second)

Source: Adapted from Holzworth (1972).

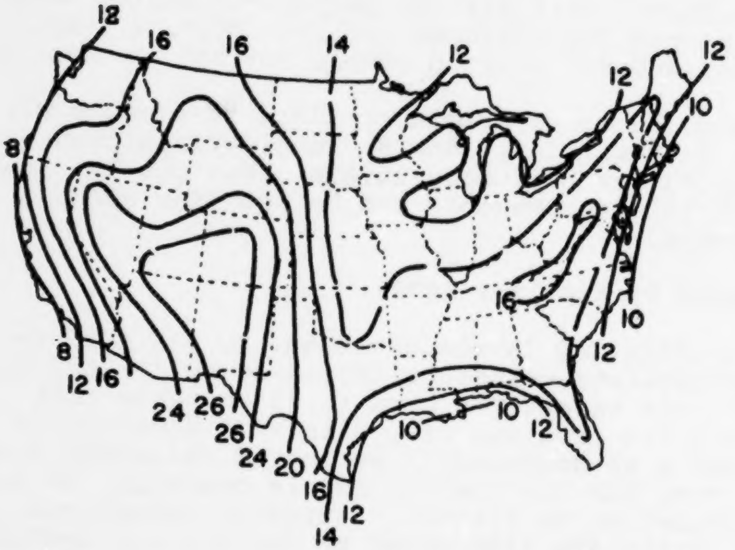
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Figure 13-2. Mean Annual Afternoon Mixing Height (in hundreds of meters)

Source: Adapted from Holzworth (1972).

Precipitation

Atmospheric pollutants in both particulate and gaseous forms are incorporated into clouds and precipitation. These pollutants can then be transported to the ground through rainfall (wet deposition). Cloud-formation processes and the consequent type of precipitation, together with the intensity and duration of precipitation, are important in determining wet deposition of pollutants.

PATTERNS AND TRENDS IN AIR QUALITY

To protect the public health and welfare, the U.S. EPA has promulgated National Ambient Air Quality Standards (NAAQS). In 1986, 75 million people lived in counties with measured air quality levels that violated the primary NAAQS for ozone (O_3) (Figure 13-3) as compared with 41.7 million people living in countries exceeding the primary NAAQS for total suspended particulates (TSP), 41.4 million people for carbon monoxide (CO), 7.5 million people for nitrogen dioxide (NO_2), 4.5 million people for lead (Pb), and 0.9 million people for sulfur dioxide (SO_2).

Although millions of people continue to breathe air that is in violation of the primary NAAQS, considerable progress is being made in reducing air pollution levels. Nationally, long-term 10-year (1977-86) improvements can be seen for all six of the above pollutants.

Total Suspended Particulate (TSP)

Annual average TSP levels decreased by 23% between 1977 and 1986, and particulate emissions decreased by 25% for the same period. The more recent TSP data (1982-86) show that concentrations are leveling off, with a 3% decrease in ambient TSP levels and a 4% decrease in estimated emissions during that time. Note that TSP air quality levels generally do not improve in direct proportion to estimated emission reductions, because air quality levels are influenced by factors not included in the emissions estimates, such as natural dust, re-entrained street dust, and construction activity. In Figure 13-4, 1986 annual geometric mean TSP concentrations are plotted for the 89 largest metropolitan statistical areas (MSAs). The highest concentrations generally were found in the industrial Midwest and arid areas of the West.

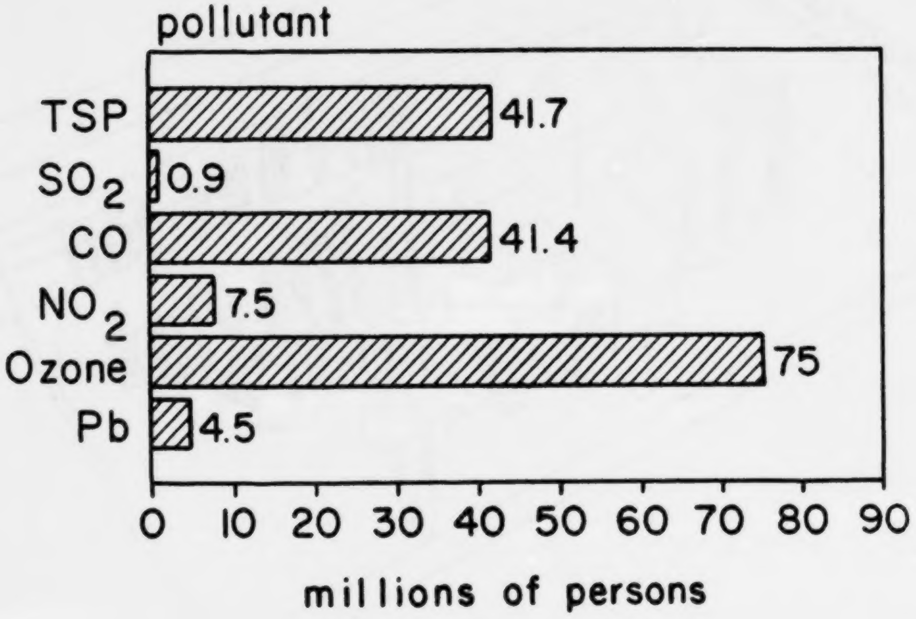

Figure 13-3. Number of Persons Living in Counties With Air Quality Levels Above the Primary National Ambient Air Quality Standards in 1986 (based on 1980 population data)

Source: U.S. EPA (1988).

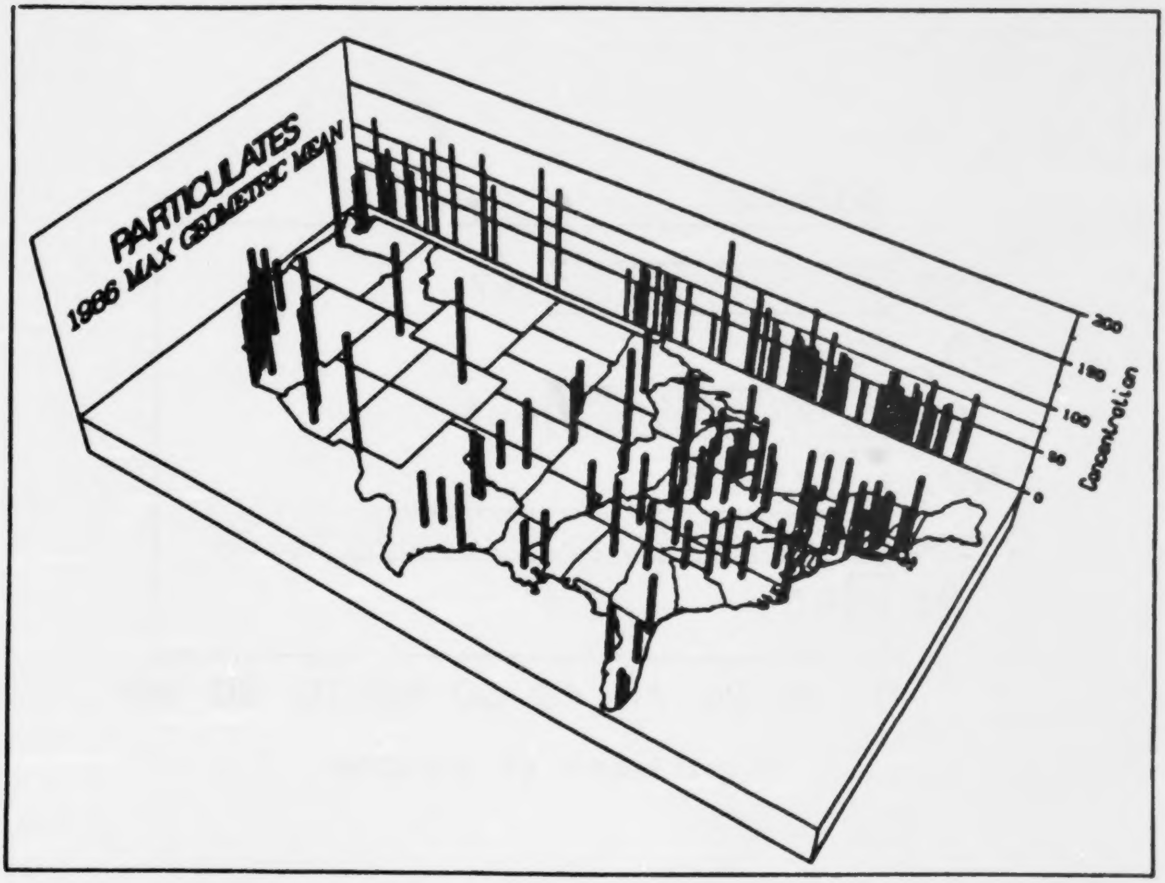

Figure 13-4. United States Map of the Highest Annual Geometric Mean TSP Concentration by Metropolitan Statistical Areas for 1986

Source: U.S. EPA (1988).

In the future, air quality may decrease as the benefits of current pollution control measures are affected by increases in population and economic growth.

Sulfur Dioxide (SO_2)

Annual average SO_2 levels decreased 37% from 1977 to 1986, improving at a rate of approximately 4% per year. An even greater improvement was observed in the estimated number of exceedances of the 24-hour standard for SO_2 concentration, which decreased by 98%. These decreases correspond to a 21% drop in sulfur dioxide emissions during this 10-year period. However, most of the exceedances and the improvements occurred at source-oriented sites, particularly a few smelter sites.

In Figure 13-5, the 1986 annual arithmetic mean SO_2 concentration is plotted for the 89 largest MSAs. The higher concentrations were found in the heavily populated Midwest and Northeast. All urban areas had ambient air quality concentrations lower than the current annual primary standard of 0.03 ppm.

Ozone (O_3)

Nationally, between 1977 and 1986, the annual average of the daily maximum ozone values decreased by 20%; between 1979 and 1986, O_3 levels decreased by 13%. Emissions of volatile organic compounds (VOCs), ozone precursors, decreased by 19% from 1977 to 1986, and by 20% from 1979 to 1986. The estimated number of exceedances of the ozone standard decreased by 38% between 1979 and 1986. In Figure 13-6, the 1986 annual average of the daily maximum O_3 concentrations is plotted for the 89 largest MSAs. Many of these areas did not meet the 0.12 ppm primary NAAQS. The highest concentrations were in southern California, but high levels also persisted in the Texas gulf coast, the northeast corridor, and other heavily populated regions.

Acid Deposition

Widespread concern exists concerning the effects of acid deposition on the environment. With the present monitoring network density in eastern North America, it is now possible to quantify regional patterns of concentration and deposition of sulfate, nitrate, and hydrogen ions, primary constituents of acid deposition. In Figures 13-7 through 13-9, isopleth maps show the

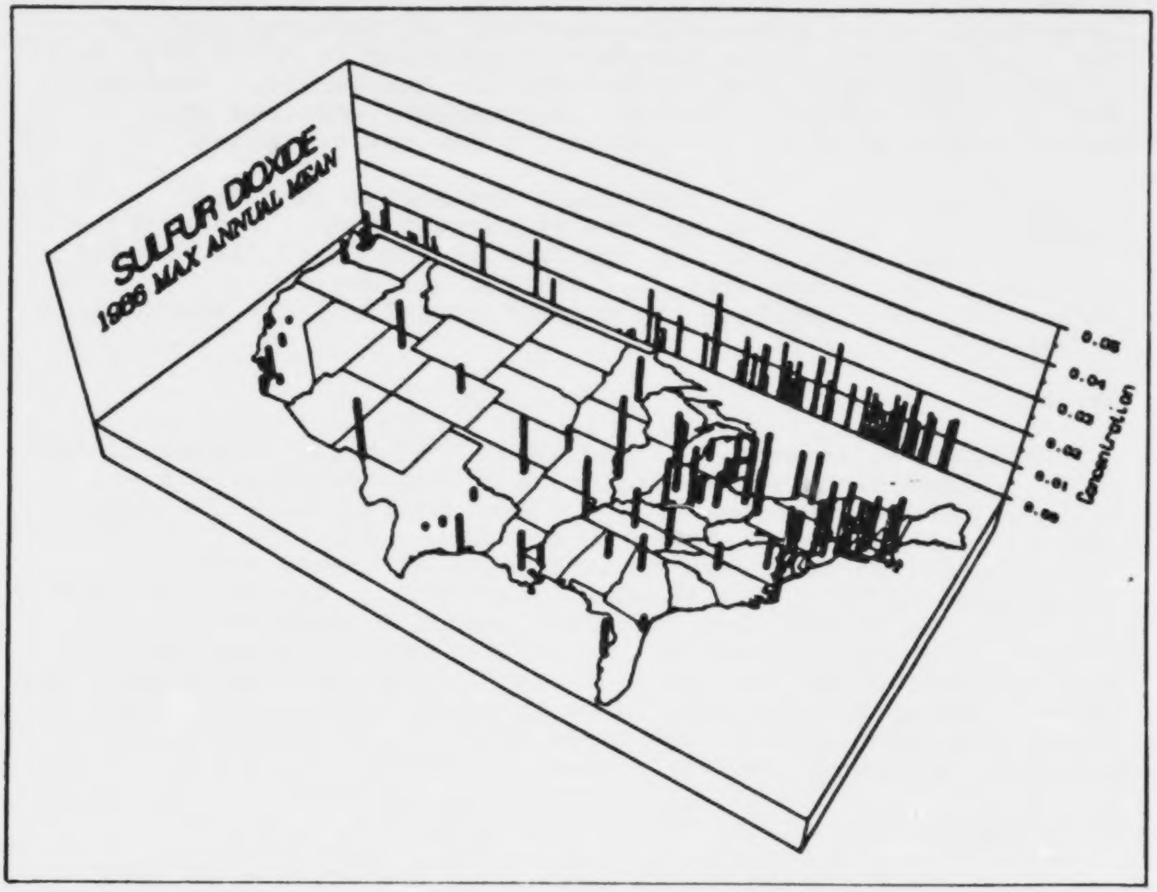
SULFUR DIOXIDE
1986 MAX ANNUAL MEAN
0.05
0.04
0.03
0.02
0.01
0.00
Concentration

Figure 13-5. United States Map of the Highest Annual Arithmetic Mean SO_2 Concentration by Metropolitan Statistical Areas for 1986

Source: U.S. EPA (1988).

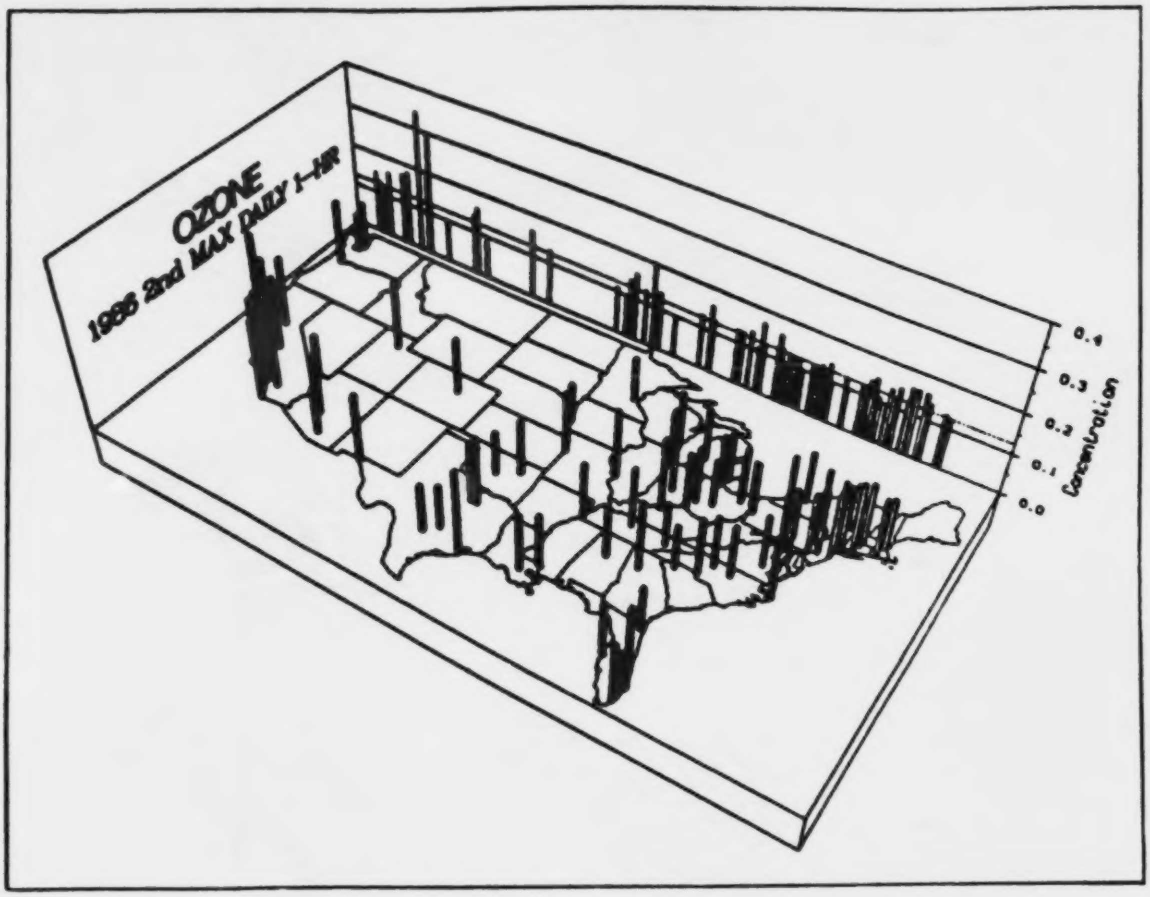
OZONE
1986 2nd MAX DAILY 1-HR
0.4
0.3
0.2
0.1
0.0
Concentration

Figure 13-6. United States Map of the Highest Second Daily Maximum 1-hour Average O_3 Concentration by Metropolitan Statistical Areas for 1986

Source: U.S. EPA (1988).

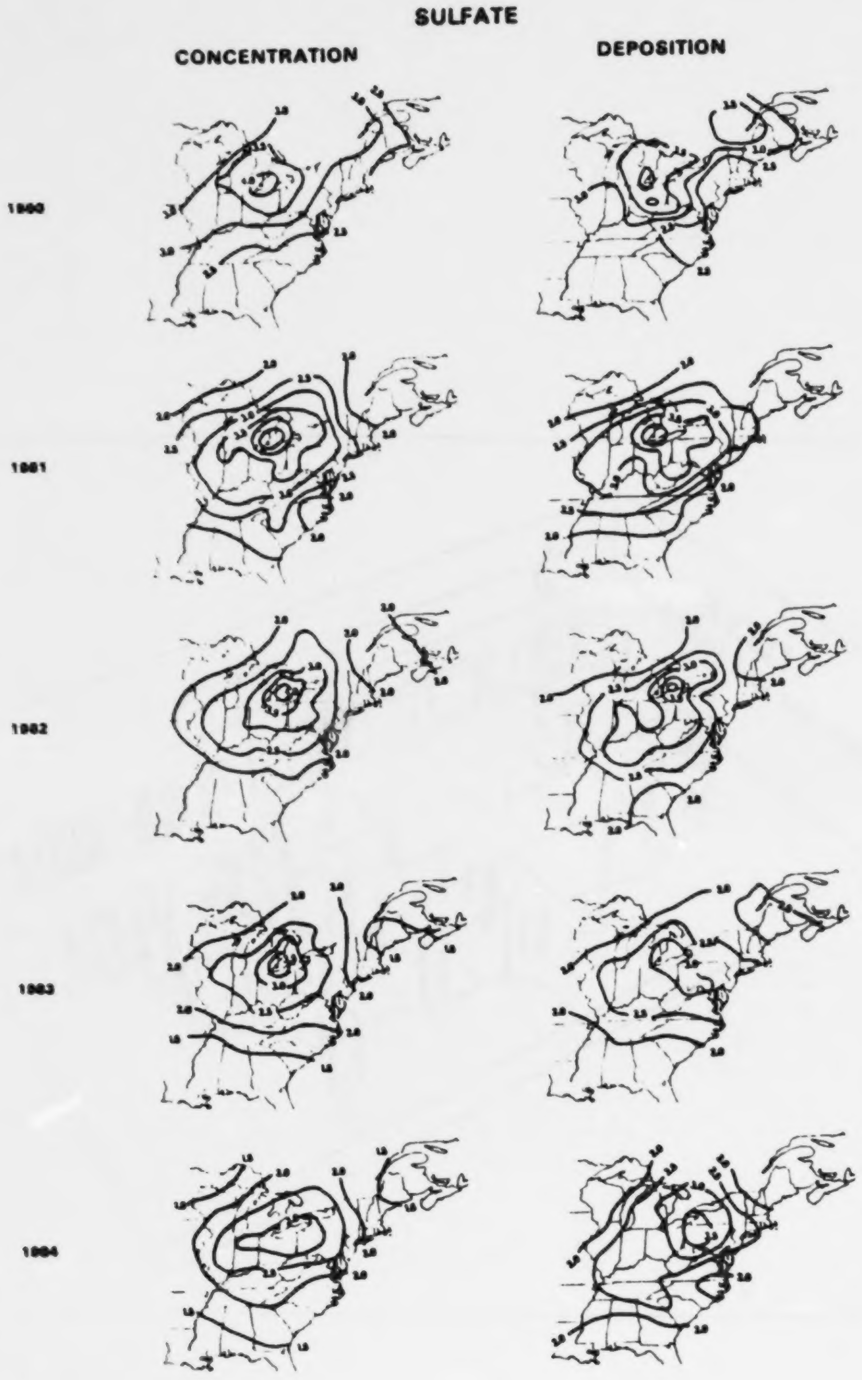
SULFATE
CONCENTRATION
DEPOSITION
1980
1981
1982
1983
1984

Figure 13-7. Isopleth Maps of Average Annual Concentrations (mg l^{-1}) and Total Annual Deposition (g m^{-2}) of Sulfate in 1980-84

Source: Seilkop and Finkelstein (1987).

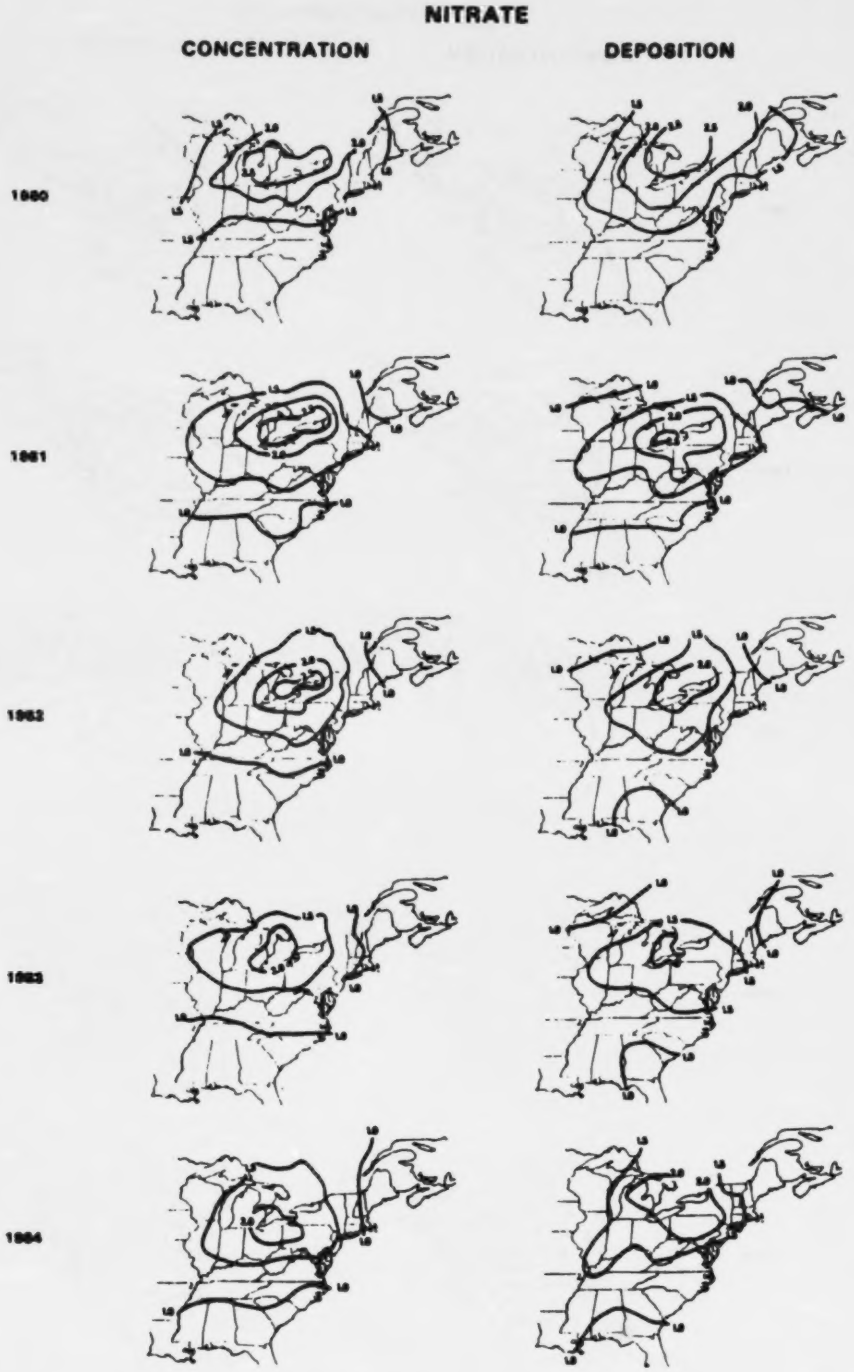
NITRATE
CONCENTRATION
DEPOSITION
1980
1981
1982
1983
1984

Figure 13-8. Isopleth Maps of Average Annual Concentration (mg l^{-1}) and Total Annual Deposition (g m^{-2}) of Nitrate in 1980-84

Source: Seilkop and Finkelstein (1987).

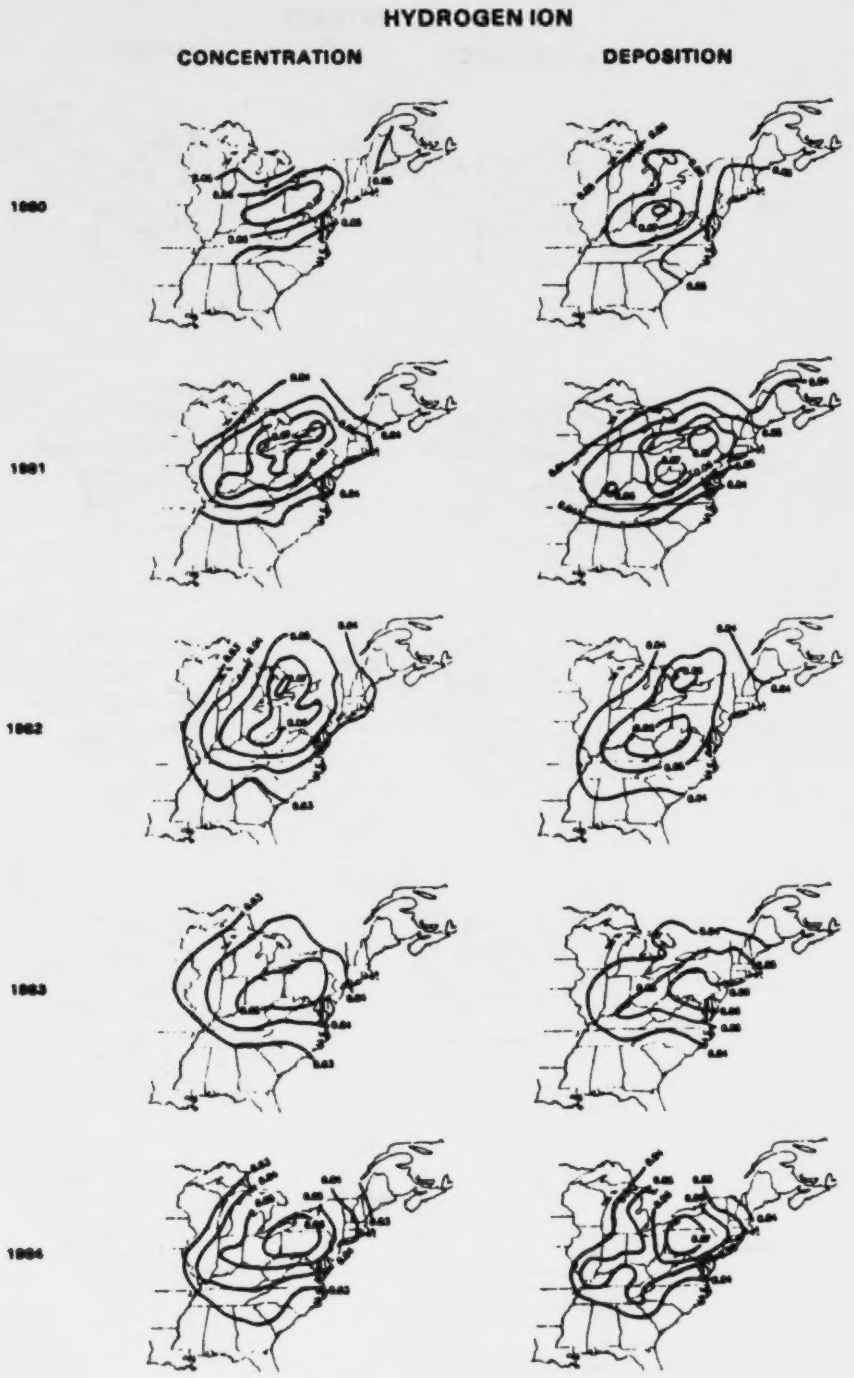
HYDROGEN ION
CONCENTRATION
DEPOSITION
1980
1981
1982
1983
1984

Figure 13-9. Isopleth Maps of Average Annual Concentration (mg l^{-1}) and Total Annual Deposition (g m^{-2}) of Hydrogen Ion in 1980-84

Source: Seilkop and Finkelstein (1987).

geographic pattern of acid deposition, as reflected by the concentration and deposition of these three species (Seilkop and Finkelstein, 1987).

For the relatively short period of 1980 through 1984, evidence indicates a 15 to 20% decrease in the total deposition and average concentration of sulfate, nitrate, and hydrogen ions in precipitation falling over eastern North America. These decreases occurred in the regions of maximum deposition and were most dramatic between 1981 and 1983. Evidence indicates increased levels of these species in 1984, although these concentrations were still less than those observed in 1980 and 1981. The observed decreases correspond with reported reductions in the U.S. emissions of sulfur oxides (SOx) and nitrogen oxides (NOx), and sulfate and nitrate precursors. However, the emission figures are subject to estimation error and should be used cautiously (Seilkop and Finkelstein, 1987).

STUDIES OF CLIMATE CHANGE AND AIR QUALITY

Some of the climate factors that could affect air quality are listed in Table 13-1. To explain these relationships for this report, EPA sponsored two projects to identify the potential impacts of climate change on air quality:

1. Climate Change and Its Interactions with Air Chemistry: Perspectives and Research Needs - Penner, Connell, Wuebbles, and Covey, Lawrence Livermore National Laboratory.

2. Examination of the Sensitivity of a Regional Oxidant Model to Climate Variations - Morris, Gery, Liu, Moore, Daly, and Greenfield - Systems Applications, Inc.

Climate Change and Its Interactions With Air Chemistry

Penner et al. conducted a literature review of studies on the relationship of climate and air quality. They also organized a workshop on the issue.

Effect of Climate Change on Ozone Formation

Changes in ventilation, circulation, precipitation, and other aspects of climate affect the concentrations of the ozone precursors VOCs and NOx. Climate changes can also increase or decrease the rates at which these precursors react to form ozone. The effects of change in global temperature and in stratospheric ozone concentration on tropospheric ozone precursor

Table 13-1. Climate Change Factors Important for Regional Air Quality

A CHANGE IN...

1. the average maximum or minimum temperature and/or changes in their spatial distribution leading to a change in reaction rates and the solubility of gases in cloud water.
2. stratospheric O_3 leading to a change in reaction rates.
3. the frequency and pattern of cloud cover leading to a change in reaction rates and rates of conversion of SO_2 to acid deposition.
4. the frequency and intensity of stagnation episodes or a change in the mixing layer leading to more or less mixing of polluted air with background air.
5. in background boundary layer concentrations of water vapor, hydrocarbons, NOx, and O_3 leading to more or less dilution of polluted air in the boundary layer and altering the chemical transformation rates.
6. the vegetative and soil emissions of hydrocarbons and NOx that are sensitive to temperature and light levels, leading to changes in their concentrations.
7. deposition rates to vegetative surfaces whose absorption of pollutants is a function of temperature, light intensity, and other factors, leading to changes in concentrations.
8. energy usage, leading to a change in energy-related emissions.
9. aerosol formation, leading to changes in reaction rates and the planetary albedo (reflectivity).
10. circulation and precipitation patterns leading to a change in the abundance of pollutants deposited locally versus exported off the continent.

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[a] Adapted from Penner et al. (1988).

concentrations, reaction rates, and tropospheric ozone concentrations are discussed below.

Temperature Change

Studies of the Effects of Temperature on Ozone. Smog chamber and modeling studies have shown that ozone levels increase as temperature increases. Kamens et al. (1982) have shown in an outdoor smog chamber study that the maximum ozone concentration increases as the daily maximum temperature increases (holding light intensity constant). Their data show that there is no critical "cut-off" temperature that eliminates photochemical ozone production. Instead, a general gradient is observed as a function of temperature.

Temperature-dependent modeling studies were conducted by Gery et al. (1987). Results for New York in June 1980 are shown in Table 13-2. In general, ozone concentration increased with increasing temperature. The concentration of hydrogen peroxide (H_2O_2), a strong oxidant that converts SO_2 to sulfuric acid, was also observed to increase with higher temperatures. This is compatible with the increase in ozone because the entire photochemical reaction process is accelerated when temperature rises. As a result, cities currently violating the ozone NAAQS will be in violation to a greater degree in the future, and cities that are complying with the NAAQS now could be forced out of compliance just by a temperature increase. Figure 13-10 shows the predicted increase in ozone for two temperatures increases in Los Angeles, New York, Philadelphia, and Washington.

Modeling studies by Penner et al. have shown that the effect temperature has on ozone formation also depends on the ratio of volatile organic compounds to nitrogen oxides, both of which are ozone precursors. Figure 13-11 shows that ozone levels will generally go up, except in areas where the ratio of VOCs to NOx is low.

Temperature change has a direct effect on ozone concentrations because it increases the rates of ozone-forming reactions. However, temperature rise can also affect ozone formation by altering four other aspects of climate or the atmosphere: cloud cover, frequency and intensity of stagnation periods, mixing layer thickness, and reactant concentrations.

Effect of Changes in Cloud Cover. The reduction in light intensity caused by increased cloud cover can reduce ozone production. Penner et al. (1988) calculate that a reduction in

Table 13-2. Maximum Hourly Concentrations and Percentage Changes for Ozone, H_2O_2, and PAN for the Future Sensitivity Tests Using an EKMA Model for the Simulation of June 24, 1980, New York

Ozone

	Concentration (ppm)			Percent change (from base)		
Change in Temp (C)	0	+2	+5	0	+2	+5
Stratospheric Ozone[a]						
Base	0.125	0.130	0.138	--	4.0	10.4
-16.6%	0.150	0.157	0.167	20.0	25.6	33.6
-33.3%	0.165	0.170	0.178	32.0	36.0	42.4

Hydrogen Peroxide (H_2O_2)

Change in Temp (C)	Concentration (ppb)			Percent change (from base)		
Stratospheric Ozone[a]						
Base	0.05	0.06	0.08	--	20.0	60.0
-16.6%	0.43	0.58	0.84	760.0	1060.0	1580.0
-33.3%	3.08	3.31	3.60	6060.0	6520.0	7100.0

Peroxyacetyl Nitrate (PAN)

Change in Temp (C)	Concentration (ppb)			Percent change (from base)		
Stratospheric Ozone[a]						
Base	3.98	3.50	2.79	---	-12.1	-29.9
16.6%	5.85	5.26	4.34	47.0	32.2	9.1
-33.3%	7.59	6.73	5.49	90.7	69.1	37.9

[a] Base refers to the present stratospheric ozone column. The -16.6 and -33.3% refer to a depletion of the base value. Ultraviolet light will increase with the depletion.

Source: Gery et al. (1987).

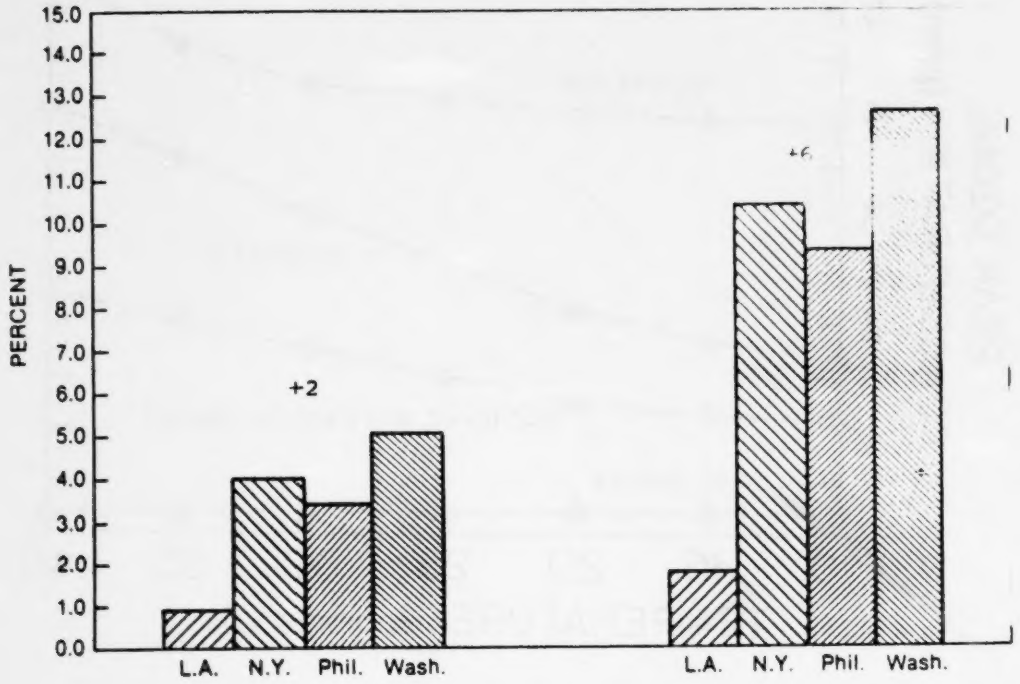

Figure 13-10. Percent increase in predicted ozone over future base case (0.12 ppm) for tow temperature increases in four cities.

Source: Gery (1987).

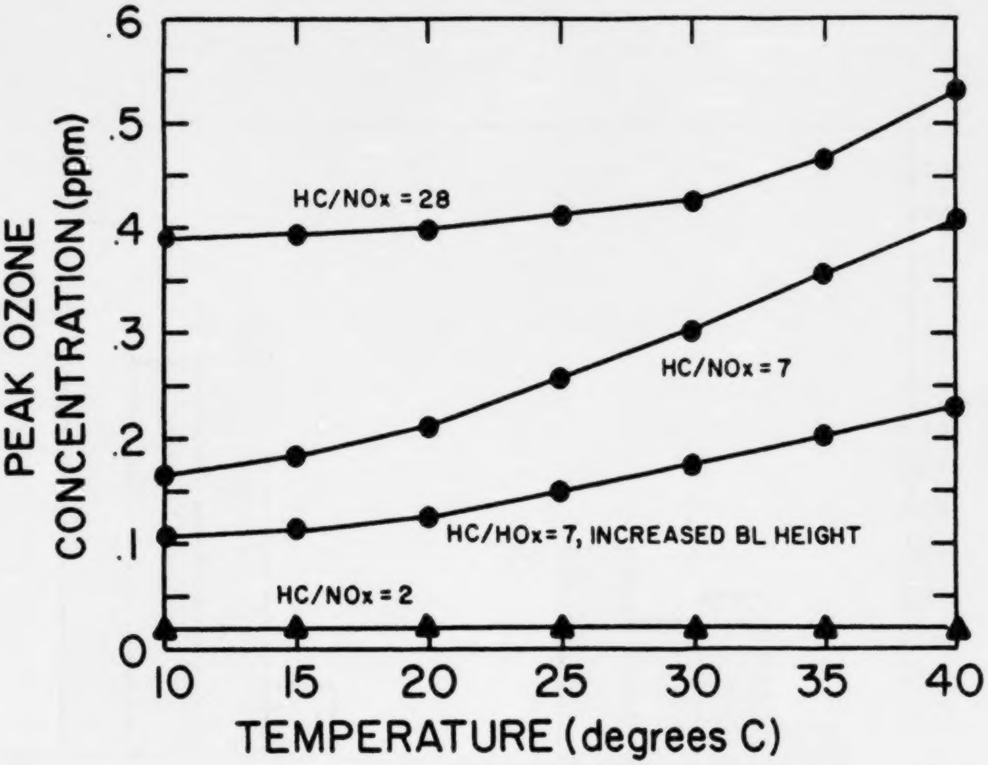

Figure 13-11. The effect of temperature on the peak O_3 concentrations predicted in a box model calculation of urban O_3 formation. Calculations are shown for three hydrocarbon tc NOx ratios. The effect of increasing the boundary layer depth for the case with a hydrocarbon to NOx ratio of 7 is also shown

Source: Penner et al. (1988).

light intensity of 50% throughout the day will reduce the ozone formation. However, the magnitude of ozone reduction depends on the time of day when the cloud cover occurs. If clouds occur in the afternoon or evening, little effect is observed in the ozone production, but if clouds occur during the morning hours, photochemical reactions are slowed, and less ozone is produced. Although a global temperature change would affect cloud cover, the type and direction of the change are unknown.

The Penner et al. study assumes that cloud cover causes an equal decrease in all wavelengths of solar radiation. However, clouds are not expected to cause an equal decrease at all wavelengths. Solar radiation is needed to form ozone. Since Penner et al. may have underestimated the intensity of some wavelengths of light, they may have overestimated the decrease in ozone production.

Effect of Water Vapor. Water vapor is involved in the formation of free radicals (reactive compounds) and hydrogen peroxide, which are necessary for the formation of ozone. Global increases in temperature are expected to raise tropospheric water vapor levels.

If sources of water vapor are not perturbed by vegetative changes, and if global circulation patterns do not significantly affect precipation events (an unlikely assumption), then global water vapor levels are expected to increase with increasing temperature. A temperature increase of 2° could raise the water vapor concentration by 10-30% (Penner et al., 1988). This change should affect both oxidant formation and sulfur dioxide oxidation (acid deposition).

Smog chamber studies have shown that at high pollutant levels, increases in water vapor can significantly accelerate both the reaction rates of VOCs and the rate of oxidant formation (Altshuller and Bufalini, 1971). In the boundary layer of the troposphere, Walcek (1985) has shown with the use of a regional acid deposition model (RADM) that the ozone, hydrogen peroxide, and sulfate production rates all increase with increasing water vapor.

Effect of Changes in Frequency and Intensity of Stagnation Periods. As noted previously, high-pressure systems significantly enhance ozone formation potential. During a high-pressure episode, pollutants are exposed to high temperatures and prolonged irradiation (Research Triangle Institute, 1975), resulting in high levels of ozone. If the intensity and frequency of high-pressure episodes increase with global warming, then ozone levels can be expected to be even higher.

Effect of Changes in Mixing Layer Thickness. As shown in Figure 13-10, increases the mixing layer height decreases ozone formation, presumably because there are less ozone precursors per volume of atmosphere. An increase of global temperature would probably lead to a increase in average mixing depths due to greater convection, which raises the mixing depth and increases mixing.

Effect of Changes in Reactant Concentrations. The concentrations of ozone precursor pollutants (VOCs, NOx) play a large part in determining the amount of ozone produced. With increasing temperature, both natural and anthropogenic emissions of these precursors are expected to increase, so ozone production should increase.

Lamb et al. (1983) have shown that natural hydrocarbon (VOC) emissions from deciduous forests would increase by about a factor of three. Emissions of NOx from powerplants would grow due to a greater demand for electricity during the summer months. Evaporative emissions of VOCs from vehicles and refueling would also be expected to rise with warmer temperatures. However, exact predictions of the effects of all these factors on ozone formation are difficult to make because the relationship between precursor emissions and ozone is extremely complex and not fully understood and because increases in emissions are difficult to quantify.

An example of this complex relationship between ozone and its precursors is shown in Figure 13-12. At high VOC levels and low NOx, adding or reducing VOCs has very little effect on ozone formation. Likewise, when NOx concentrations are high and VOC concentrations are low, increasing NOx reduces ozone formation while lowering NOx increases ozone formation. Thus, VOCs and NOx must be examined together when considering any ozone reduction strategy based on controlling ozone-forming precursors.

Stratospheric Ozone Change

Changes in stratospheric ozone concentration can also affect tropospheric ozone formation because stratospheric ozone regulates the amount of ultraviolet (UV) radiation available for producing ozone in the troposphere. Stratospheric ozone absorbs UV light from the sun and decreases the UV energy striking the Earth's surface. When stratospheric ozone is depleted by the chlorofluorocarbons (CFCs) generated by man, more UV reaches the

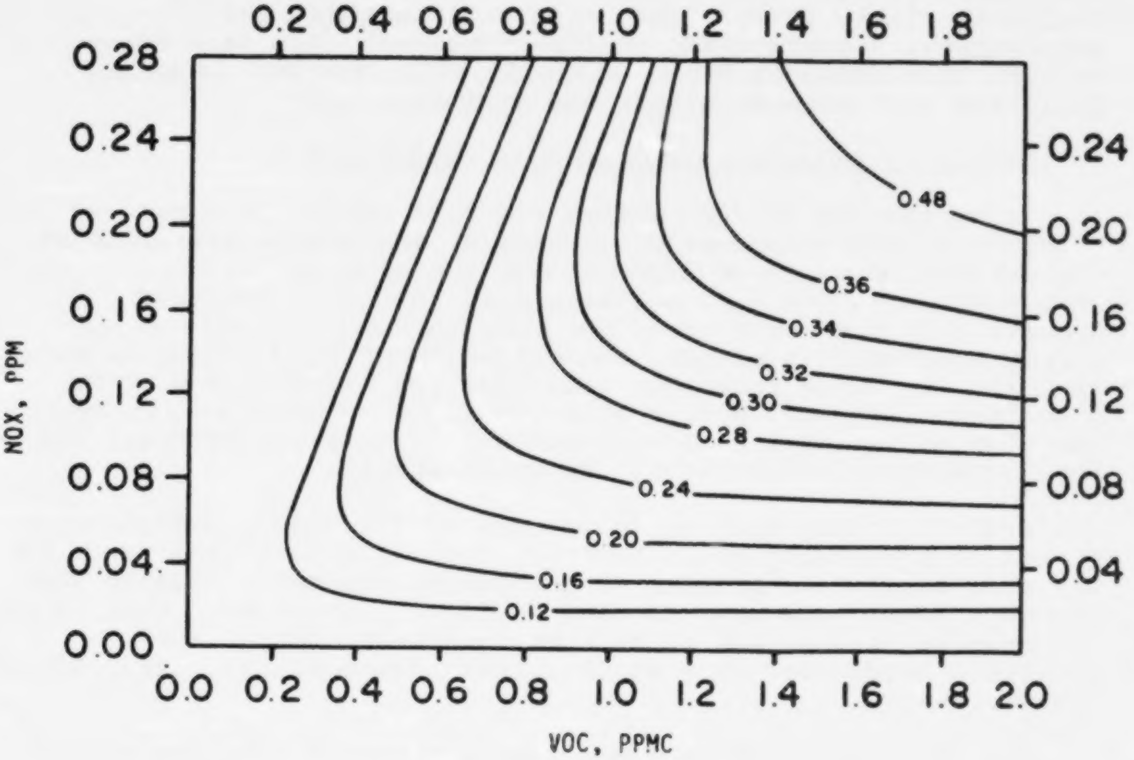

Figure 13-12. Ozone Isopleths as a Function of NOx and Volatile Organic Compounds (VOCs)

Source: Dodge (1977).

Earth's surface, which increases the photolysis rates of compounds that absorb solar radiation (nitrogen dioxide, formaldehyde, acetaldehyde, ozone, and hydrogen peroxide).* Faster photolysis produces more free radicals (high-energy species) that increase the amount of smog. Thus, less stratospheric ozone will lead to enhanced ozone formation in the troposphere.

Modeling results for New York from Gery et al. (1987) show that tropospheric ozone increased when stratospheric ozone decreased (Table 13-2). They also show that H_2O_2 and peroxyacetyl nitrate (PAN) yields increased. H_2O_2 is a strong oxidant that converts SO_2 to sulfuric acid, and PAN is an air pollutant that damages plants and irritates eyes.

Effect of Climate Change on Acid Deposition

Rainwater and surface waters are more acidic than natural background levels because of industrial and mobile emissions of SO_2 and NOx, which form sulfuric and nitric acids in the atmosphere. In the air, sulfuric acid (H_2SO_4) is produced primarily by the reaction of SO_2 with hydroxyl radicals (high-energy species); in clouds, the oxidation of SO_2 to H_2SO_4 is more complex, involving reactions with hydrogen peroxide and other dissolved oxidants. Nitric acid (HNO_3) is produced in air by the reaction of hydroxyl radicals with NOx. The exact pathways for the formation of these acids are quite complex.

Organic acids, such as formic and acetic acids, are also formed in the atmosphere. However, their relative importance to the acid deposition problem is unknown at present. Because they are weak acids (compared to H_2SO_4 and HNO_3), their contribution to the problem is expected to be much less than that of the inorganic acids (Galloway et al., 1982; Keene et al., 1983, 1984; Norton, 1985).

The acids produced in the atmosphere can be "dry deposited" to the earth's surface as gases or aerosols, or they can be "wet deposited" as acid rain. Changes in total acid levels depend on changes both in atmospheric chemistry and changes in precipitation. Wet deposition is affected most by the amount, duration, and location of precipitation. Since the direction of regional precipitation changes is not known, it is not known whether acid rain will increase or decrease in the future.

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*Photolysis is the breakdown of chemicals as a result of the absorption of solar radiation.

However, many of the same factors that affect ozone formation will also affect the total deposition of acids.

Temperature Change

Higher temperatures accelerate the oxidation rates of SO_2 and NOx to sulfuric and nitric acids. Gery et al. (1987) have shown that a temperature rise would also speed the formation of H_2O_2, further increasing the conversion of SO_2 to sulfuric acid (Table 13-2). Considering only the chemistry occurring with a 10°C temperature rise, SO_2 oxidation increased 2.5 times. It is likely that oxidation would also increase with a smaller temperature. The limiting factor in the oxidation of SO_2 appears to be the availability of H_2O_2. The model also suggested that a temperature increase would cause more sulfuric acid to form near the sources where SO_2 is emitted.

Effect of Global Circulation Pattern Changes. Changes in global circulation patterns will greatly affect local acid deposition, because they will alter ventilation and precipitation patterns. Galloway et al. (1984) have calculated that over 30% of the sulfur emissions from the eastern United States are transported to the north and farther east. Changes in circulation patterns would affect this transport, although the direction or magnitude of the effect is unknown.

Effects of Changes in Emissions. If electricity demand rises with rising temperatures (see Chapter 16, Electricity Demand) and if more fossil fuels are burned, SO_2 and NOx emissions would increase. An approximately 10% growth in use of electricity in the summer could increase SO_2 emissions during the summer by approximately 30%. This, in turn, would increase acid deposition.

Effects of Reduced Stratospheric Ozone. A decrease in stratospheric ozone due to CFCs will increase acid deposition because more UV radiation will be available to drive the chemical reactions. As discussed above, a modeling study by Gery et al. (1987) showed an increase in the yield of H_2O_2 when stratospheric ozone was reduced by 33%. Because H_2O_2 is a strong oxidant, SO_2 will probably also be oxidized more quickly into sulfate aerosols and acid rain, but this depends the availability of liquid water (e.g., clouds, rain).

Reduced Visibility. The growth in natural organic emissions sulfates resulting from warmer temperatures should reduce visibility. This assumes that the frequency of rain events, wind velocity, and dry deposition rates remain the same. If rain events increase, washout/rainout should increase and visibility would be better than predicted.

MODELING STUDY OF CLIMATE AND AIR QUALITY

Study Design

Morris et al. (Volume X) applied a regional transport model RTM-III to an area covering central California and a region covering the midwestern and the southeastern United States. The model was run for the present-day conditions and for a future climate with higher temperatures. For California, Morris et al. used input data from August 5-10, 1981; for the Midwest and the Southeast, they used input data from July 14-21, 1981.

The RTM-III is a three-dimensional model that represents point sources embedded in a grid framework. The model has three prognostic vertical layers and a diagnostic surface layer. This means that the surface layer is represented by actual observations. The other three layers are predicted by using the surface layer data. The photochemical reactions are based on the latest parameterized chemical mechanism.

Study Limitations

The estimates for ozone are only coarse approximations. Morris et al. used the National Acid Precipitation Assessment Program (NAPAP) emissions data of 1980, but appear to underestimate actual ratios of VOCs to NOx as measured in urban areas. Ching et al. (1986) state that for most cities, the NAPAP data underestimate VOC emission values by a factor of three or more.

The model simplified some reactions of the hydrocarbons (VOCs) because the chemistry is not well known. The model ignored future increases in emissions that would occur with increased temperatures.

This study did not estimate climate induced alterations in most meteorological variables, except temperature and water vapor, which is an oversimplification. For example, this study assumed that the mixing heights remain unchanged for the temperature increase scenario; in reality, mixing heights could increase with rising temperature. Holding the mixing heights constant probably overemphasized the importance of temperature in oxidant production, because an increased mixing layer depth might have had a dilution effect.

Study Results

Central California Study

Table 13-3 summarizes the results from the base case scenario and a climate sensitivity scenario that used a 4°C temperature increase and an attendant increase in water vapor concentration. All of the days studied show a larger area exposed to high levels of ozone. An increase in temperature may lengthen the duration of high ozone levels, although the maximum levels may be the same. Figure 13-13 illustrates the August 6 base case and climate sensitivity case. The temperature change increased the August 6 maximum ozone concentration from 15 parts per hundred million (pphm) to 18 pphm, a 20% increase in ozone. The area in which the NAAQS was exceeded almost doubled from 3,700 to 6,600 km^2.

The temperature increases in the two main cities in the San Joaquin Valley (Fresno and Bakersfield) resulted in an approximately 0.5 pphm increase (approximately 8%) in maximum daily ozone concentration. In regions farther away from the emissions, such as the Sierra Nevada Mountains, little change in ozone levels was observed with the increased temperature.

Midwest and Southeast Study

The results from applying RTM-III to the midwestern and southeastern areas are shown in Table 13-4. On one particular day (July 16) raising the temperature caused maximum ozone to increase from 12.5 pphm to 13.0 pphm (Figure 13-14). Although this is only a slight increase (0.5 pphm), the predicted area of exceedance of the ozone NAAQS increased by almost a factor of three, from 9,800 to 27,000 km^2. The differences occurred mainly in the upper Midwest.

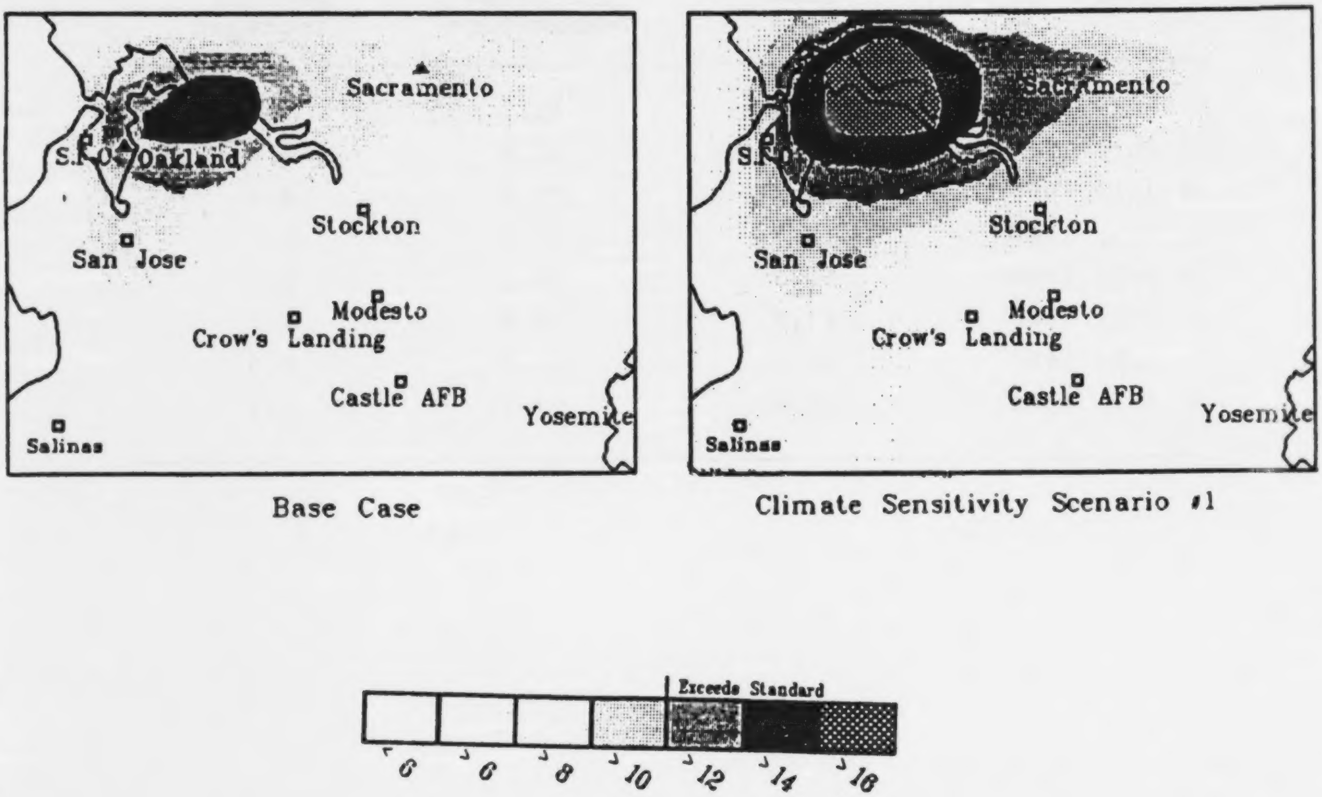
Population Exposure

As discussed above, both study domains show a significant area that is exposed to higher levels of ozone when the temperature is increased. Data taken from the 1980 census from central California and the midwestern and southeastern areas were used to determine the number of people exposed to ozone for the base case and temperature rise scenarios. Table 13-5 presents the number of people-hours of exposure to ozone concentrations exceeding 8, 12, and 16 pphm. These estimates of human exposure were generated by multiplying the number of people in the grid cells by the total number of hours that the predicted hourly

Table 13-3. Maximum Daily Ozone Concentrations Predicted by the RTM-III for Each Day of the Central California Modeling Episodes for the Base Case and the Case of Climate Sensitivity to Increased Temperature

	Maximum Daily Ozone Concentration (pphm)		
Day of Episode	Base Case	Increased Temperature	Percent Increase
August 5, 1981	11.8	12.1	3
August 6, 1981	15.0	18.0	20
August 7, 1981	11.7	13.1	12
August 8, 1981	13.5	13.7	2
August 9, 1981	10.5	11.2	7
August 10, 1981	9.1	9.18	8

Source: Morris et al. (1988).


Sacramento
S.F.
Oakland
Stockton
San Jose
Modesto
Crow's Landing
Castle AFB
Yosemite
Salinas
Sacramento
S.F.
Stockton
San Jose
Modesto
Crow's Landing
Castle AFB
Yosemite
Salinas
Exceeds Standard
<6
>6
>8
>10
>12
>14
>16

Base Case

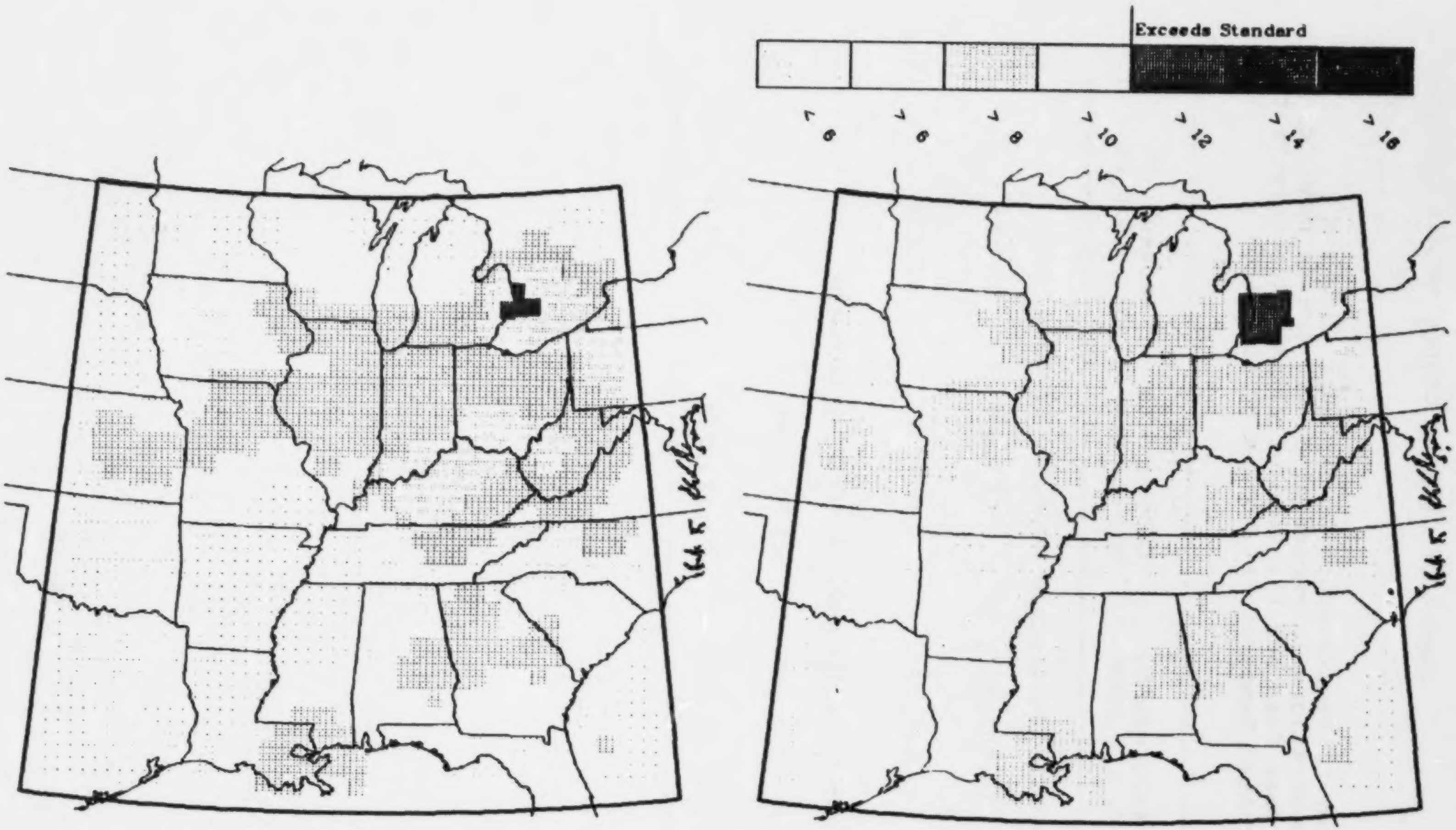
Climate Sensitivity Scenario #1

Figure 13-13. Comparison of Predicted Maximum Daily Ozone Concentrations (pphm) for the Base Case and Climate Sensitivity Scenario No. 1 (temperature and water increase) for August 6, 1981

Source: Morris et al. (1988).

Table 13-4. Maximum Daily Ozone Concentrations Predicted by the RTM-III for Each Day of the Midwestern/Southeastern Episode for the Base Case and the Case of Increased Temperature (Morris et al. 1988).

Date	Maximum Daily Ozone Concentrations (pphm) Base Case	Increased Temperature	Percent Increase
14 July 1980	11.3	11.3	0.0
15 July 1980	11.5	11.9	3.5
16 July 1980	12.5	13.0	4.0
17 July 1980	11.7	12.0	2.6
18 July 1980	11.2	12.1	8.0
19 July 1980	13.8	14.8	7.2
20 July 1980	11.1	11.2	0.9
21 July 1980	12.6	12.3	-2.4


Exceeds Standard
< 6
> 6
> 8
> 10
> 12
> 14
> 16

Base Case

Climate Sensitivity Scenario #1

Figure 13-13. Comparison of Predicted Maximum Daily Ozone Concentrations (pphm) for the Base Case and Climate Sensitivity Scenario No. 1 (temperature and water increase) for July 16, 1980

Source: Morris et al. (1988).

Table 13-5. Number of People-Hours of Exposure to Ozone Concentrations in excess of 8, 12, and 16 pphm for the Base Case and the Case of Climate Sensitivity to Increased Temperature (Morris et al., 1988).

Scenario	Exposure to $O_3 \geq 8$ pphm	Exposure to $O_3 \geq 12$ pphm	Exposure to $O_3 \geq 16$ pphm
	Central California Modeling Episode		
Base Case	70,509,216	660,876	0
Increased Temperature	102,012,064	2,052,143	92,220
	Midwestern/Southeastern Modeling Episode		
Base Case	1,722,590,208	29,805,348	0
Increased Temperature	1,956,205,568	47,528,944	0

ozone concentration in those grid cells exceeded the 8, 12, or 16 pphm levels. Actual exposure levels may be less because indoor levels are generally lower than ambient air levels.

ECONOMIC, ENVIRONMENTAL, AND ECOLOGICAL IMPLICATIONS

Ozone

A national standard for ambient levels of ozone was established with the original Clean Air Act in 1972 along with standards for five other pollutants. While headway has been made in meeting all these national air quality standards, progress in meeting the ozone standard has been particularly slow and frustrating for concerned lawmakers and environmental officials at all levels of government. At the end of 1987, the date anticipated in the Act for final attainment of the ozone standard more than 60 areas had not met the standard. In recent years, the number of nonattainment areas has fluctuated with meteorology often overwhelming the progress being made through reduced emissions. Thus "bad" weather (summertime conditions favorable to ozone formation) in 1983 led to an increase in the number of nonattainment areas while "good" conditions in 1986 led to a decline in the number of areas.

An increase in ozone levels due to climate change is important for several reasons:

- Ozone levels in many areas are just below the current standard. Any increase in ozone formation is likely to push levels above the standard.
- Many inexpensive controls for ozone are already in place in nonattainment areas. Increases in ozone levels will require relatively expensive measures to sufficiently reduce ozone precursors to attain the standard.
- The standard itself is defined in terms of the highest levels of ozone experienced in an area, not average levels. (As a yearly average, no area of the country would exceed the standard of 0.12 ppm.) Thus, a factor such as temperature that may have a modest effect on average levels of ozone formation may have a much more significant effect on peak levels.

A rough estimate of each of these factors can illustrate the potential policy problems created by a rising temperature scenario. The data in Figure 13-11 suggest that 5°C degree rise in temperature may lead to an increase in peak ozone concentrations of around 10%. We can then ask what impact a 10% increase in peak ozone levels would have on the number of potential ozone violations. In the 1983-1985 period for example, 68 areas showed measured exceedances of the ozone air quality standards (for technical and legal reasons not all these areas were officially designated nonattainment areas.) A 10% increase in ozone levels in that period doubled the number of nonattainment areas to 136. This would include 41 new MSAs added to the list and 27 nonMSAs. These new nonattainment areas would add most midsize and some small cities in the in the midwest, south and east to the list of nonattainment areas.

The policy implications of this should not be overstated. The temperature is predicted to rise over a number of years, and the full effect will not be felt until well into the next century. Over the next several decades, various national measures to reduce ozone precursors, such as a reduction in the volatility of gasoline, may go into effect. These would provide a cushion to marginal areas and could offset a temperature effect. However, other factors suggest that the temperature problem will persist.

Ozone levels and ozone precursors are closely related to economic expansion and population growth. Consumer solvents (e.g., paints, sprays, and even deodorants) are a major source of ozone precursors. These are very difficult to control and will undoubtedly increase in the future in areas currently attaining the standards. Growth in other sources of ozone precursors would bring many areas relatively close to the limits of the ozone standard. Gradual increases in temperature would make remaining in compliance with the standard more difficult. Although any sudden change in the number of nonattainment areas as a result of a secular trend toward increased temperature is unlikely, a number of small to midsize cities eventually may be forced to develop new control programs.

The implications of warmer temperature rise for existing nonattainment areas can also be estimated. In these areas existing and planned control measures may not be adequate to reach the standard, if additional ozone forms. In the past, EPA has attempted to project the emission reductions and costs associated with the attempts of existing nonattainment areas to reach the ozone standard. Using the same modeling approach, the effects of a temperature increase were analyzed to estimate the additional tons and costs associated with a projected temperature rise. Extrapolations of existing inventories to the year 2000 suggest that higher temperatures could require an additional reduction of 700,000 tons of VOC from an inventory of about 6 million tons. Given that most current nonattainment areas will have already implemented the most inexpensive measures, these additional reductions may cost as much as $5,000 per ton year. Their aggregate cost could be as much as $3.5 billion each year.

These conclusions should be viewed as very preliminary. Nonetheless, they demonstrate that the potential economic consequences for an already expensive program to combat ozone could be significant.

Acid Rain

The global climate change and acid rain issues are likely to collide in the near future for several reasons:

First, emissions from fossil fuel powerplants both influence acid rain and contribute to global warming. In the future, global warming may increase energy demand and associated emissions. Because the growth of northern electricity demand may be less than anticipated, regional shifts in the growth emissions may occur in the future.

Second, global climate change will influence atmospheric reaction rates and the deposition and form of acidic material. It is conceivable that regions of high deposition may shift or that more acid rain may be transported off the North American continent. Strategies that seek to control powerplants in regions near sensitive areas may or may not be as effective, as global climate change occurs.

Third, global climate change will alter the impacts of acid rain on ecological and other systems in as yet unpredictable ways. For example:

- Changes in the amount of rainfall may dilute the effect of acid rain on many sensitive lakes.
- Changes in clouds will alter the fertilization of high elevation forests.
- Changes in humidity and frequency of rain may alter degradation rates for materials.
- Increased midcontinental dryness would alter the amount of calcium and magnesium in dust, neutralizing impacts on soils.

- Increased numbers of days without frost would decrease forest damage associated with frost and overfertilization by atmospheric nitrogen.

- Changes in snowpack and the seasonality of rainfall will change acid levels in streams and alter the timing and magnitude of spring shocks an aquatic species.

Finally, solutions to both problems are inextricably linked because the implementation of acid rain control measures and ? life extension programs of many utilities may not occur until after the year 2010, that is when global warming may be fully recognized. Some solutions, e.g., SO_2 scrubbers and clean coal technologies, may abate acid rain levels, but may do little to improve or may increase global warming. Other solutions, including increased energy efficiency and fuel switching to natural gas or renewable energy sources, may provide positive solutions to both problems.

In summary, an examination of the time horizons of importance to both acid rain and global climate change problems suggests that these two issues can no longer be viewed in isolation. Emissions, atmospheric reaction rates, pollutant transport, and environmental impacts will be altered by climate change. This suggests that a more holistic approach must be taken to air pollution problems and that proposed solutions should be evaluated on the basis of their contributions to solving both problems.

Carbon Monoxide

While global warming as a general rule will exacerbate major pollution problems, it may actually have a modest positive effect on the problem of carbon monoxide (CO) nonattainment. This is because most CO violations occur during the winter months, and that automobile CO emissions (the primary source of CO) are greatest under cold start conditions. With slightly warmer conditions overall, there should be some lessening of the CO problem.

POLICY IMPLICATIONS

The Environmental Protection Agency issues air pollution regulations to improve air quality and to protect public health and welfare. In general, current regulations to reduce oxidant levels will also provide positive benefits toward a goal of limiting the rate of growth in global warming. Other programs aimed at reducing carbon monoxide levels, particularly from mobile sources, or CFCs to protect the stratospheric ozone layer, also positively affect greenhouse gases and the rate of global warming. However, the regulatory activities of the Agency have not been retrospectively reviewed to determine their impacts on global warming. In some cases there may be important benefits; for example, current emission standards for automobiles do not encourage more efficient use of gasoline. A different form of standard, while potentially disruptive to air pollution efforts, might produce positive greenhouse gas benefits via reduced energy consumption. These types of analyses will have to be performed in the future.

Because of the climate change issue, the following are some of the more important policy issues:

- Air pollution control agencies such as EPA should undertake a broad review to determine the impact of global climate change on air pollution policies. In particular, the cost of added controls resulting from climate change should be determined, perhaps as each significant regulation is proposed or reevaluated.
- The impact of EPA regulations, particularly the impact on energy use and greenhouse gases, should be a more important weight in future regulatory decisions. Since EPA regulations often serve as models for other countries, the energy penalty, while sometimes small in the United States, may be important on a global basis.
- Future reports to Congress and major assessments of ecological effects, e.g., the 1990 Acid Deposition Assessment document, should include sensitivity analyses of alternative climates. Risk management decisions of the Agency could then be made with improved knowledge of climate impacts.

Recommendations for Further Research

Some of the key questions which need to be resolved regarding climate change and air quality include the following: How important will climate change be relative to other factors such as population growth to future air pollution problems? Is the impact of climate change likely to be significant enough so as to require totally different air pollution strategies? What mix of control strategies could be most cost effective in reducing acid rain, global warming, tropospheric ozone and other pollution problems? The research elements needed to address these issues include basic research, sensitivity analyses, full scale atmospheric modeling, and cost effectiveness studies. Examples are presented below:

Basic Research: There is an important need to understand how manmade and natural emissions of hydrocarbons and other pollutants might change in the future when temperatures, CO_2, and UV-B radiation increase and other climate parameters vary.

Sensitivity Analyses: Analyses of ozone concentrations are dependent on boundary layer height, clouds, water vapor, wind speed, UV-B radiation and other parameters. Sensitivity tests using single models could improve our understanding of the relative importance of these variables and could provide important information for general circulation modelers.

Full Scale Modeling - Complete understanding of the interactions of climate change and air quality will ultimately require that general circulation models and mesoscale chemistry models be linked in some direct or indirect manner. This will require the development of innovative approaches between the general circulation and air pollution modeling communities.

Cost Effectiveness Studies - There are currently a number of Congressional proposals to improve the Clean Air Act and to reduce global climate change. In order to assume that both air quality and global climate change goals are achieved, analyses of the cost effectiveness of alternating strategies will be necessary.

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DRAFT

CHAPTER 14

HUMAN HEALTH

FINDINGS

Global warming may lead to increases in morbidity and mortality during the summers, particularly among the elderly. These effects may be more pronounced in some regions than in others, with northern regions more vulnerable to the effects of higher temperature episodes than southern regions. Milder winters may offset increases in morbidity and mortality, although net mortality may increase. If people become acclimatized to the warmer temperatures by using air conditioning, changing work place habits, and altering the construction of homes and cities, the impact on summer mortality rates may be substantially reduced. The full scope of the impacts of climate change on human health remains uncertain and the subject for future research.

- Although there may be increases in weather-related summer deaths due to respiratory, cardio-, acular, and cerebrovascular disease, there may be decreases in weather-related winter deaths for the same diseases. In the United States, however, on average, weather-related deaths are greater in summer than in winter. Thus, global warming could produce a net increase in deaths.

- Sudden changes in temperature are correlated with increases in deaths. So if climatic variability increases, morbidity and mortality are also likely to increase. A decrease in the frequency or intensity of climate extremes is likely to be associated with a decrease in mortality and morbidity.

- Seasonal variation of fetal and infant mortality (higher in the summers, lower in the winters) is thought to be due to summertime increases in infections. The longer and hotter summers that may accompany climate change may exacerbate this effect at least in some regions.

- Vector-borne diseases, such as those carried by ticks, fleas and mosquitos, could increase in certain regions. In addition, climate change may alter habitats. For example, some forests may become grasslands, thereby modifying the incidence of vector-borne diseases.

- While uncertainties remain about the magnitude of other effects, it's climate change could have the following impacts:

- Increases in summer rainfall would multiply the amount of ragweed growing on cultivated land.
- Changes in humidity may heighten the incidence and severity of skin infections and infestations such as ringworm, candidiasis, and scabies.
- Increases in the persistence and level of air pollution episodes associated with climate change will have adverse health effects.

CLIMATE-SENSITIVE ASPECTS OF HUMAN HEALTH

Human illness and mortality are linked in many ways to the environment (Figure 14-1). Mortality rates, particularly for the aged and very ill, are influenced by the frequency and severity of extreme temperatures. The life cycles of disease-carrying insects, such as mosquitoes and ticks, are affected by changes in temperature and rainfall, as well as by modifications in habitat that result from climate change. Air pollution, frequently associated with climate change, is known to increase the incidence or severity of respiratory diseases such as emphysema and asthma. Climate variables have been implicated in affecting such chronic diseases as stroke and heart disease, such contagious diseases as influenza and pneumonia, such allergic diseases as asthma and hay fever, and such vector-borne diseases as encephalitis and Lyme disease.[*] In addition, adverse effects on reproduction, such as increased incidence of premature births, are associated with certain seasons. Table 14-1 lists the number of deaths and the number of physician visits (used to estimate the amount of illness associated with a given effect) associated with major causes of mortality and illness in the United States.

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[*] Vector-borne diseases are those that are spread to humans or animals by an insect, such as a mosquito or tick. The agent is the disease-causing organism, such as a virus, that is carried and transmitted by the vector. Some vectors, such as ticks, live on other animals, such as deer and birds, which are called hosts. For example, Lyme disease is caused by a bacteria (the agent), which is carried by a certain specie of tick (the vector), which lives on deer and mice (the hosts).

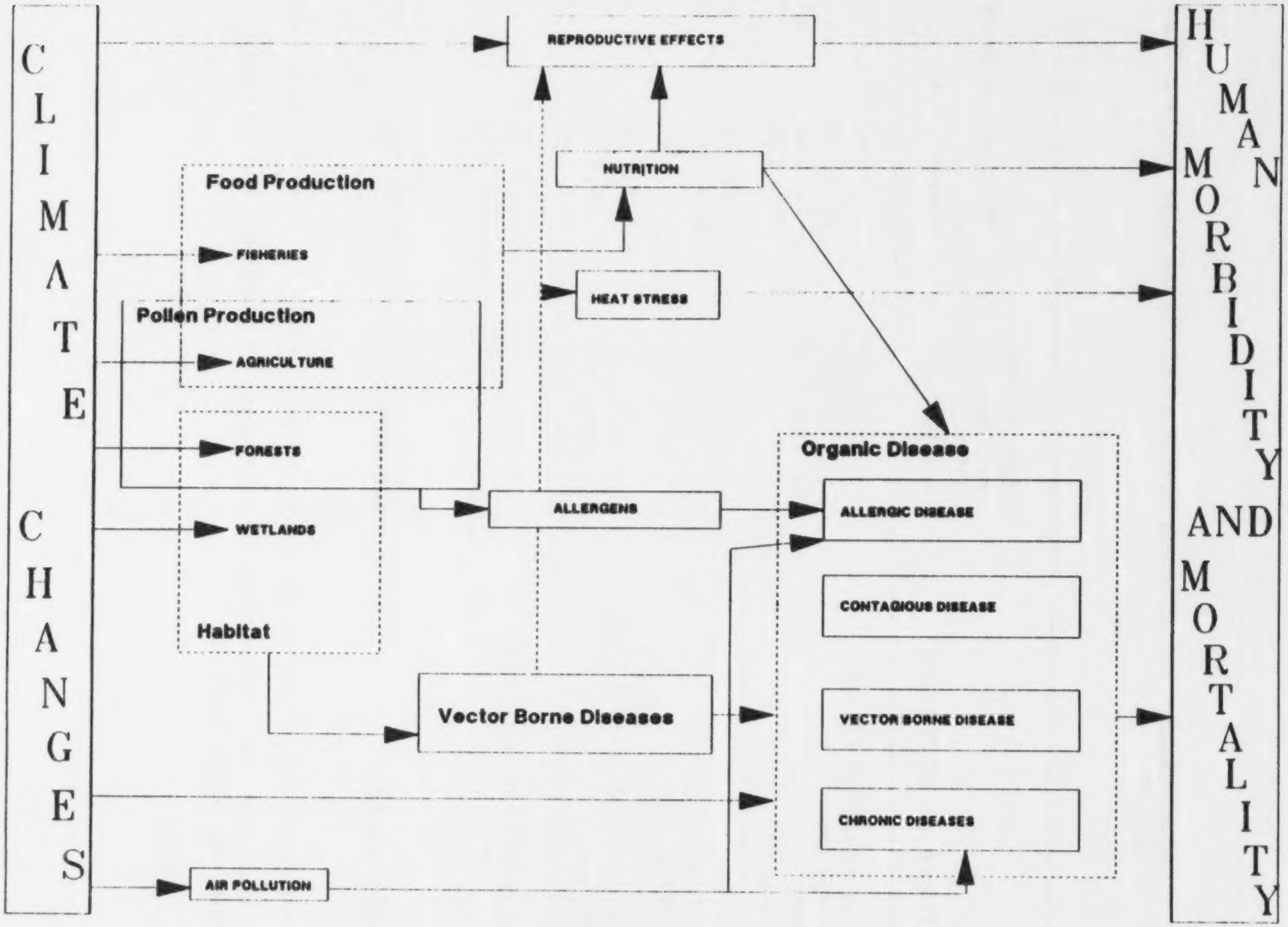
CLIMATE CHANGES
REPRODUCTIVE EFFECTS
NUTRITION
Food Production
FISHERIES
HEAT STRESS
Pollen Production
AGRICULTURE
FORESTS
WETLANDS
Habitat
ALLERGENS
Vector Borne Diseases
AIR POLLUTION
Organic Disease
ALLERGIC DISEASE
CONTAGIOUS DISEASE
VECTOR BORNE DISEASE
CHRONIC DISEASES
HUMAN MORBIDITY AND MORTALITY

Figure 14-1. Schematic of How Climatic Changes Can Impact on *Human Health*

Table 14-1. Major Causes of Illness and Mortality in the United States (1984)[a]

Cause of Illness or Mortality	Estimated Number of Physician Contacts	Estimated Mortality	
		Number	Rate/100,000
Accidents and adverse effects	70,000,000	93,520	39.6
Malignant neoplasms	20,300,000	453,660	192.1
Heart diseases	72,400,000	763,260	323.2
Suicides, homicides	-	47,470	20.1
Chronic liver disease and cirrhosis	1,400,000	26,690	11.3
Cerebrovascular diseases	9,100,000	154,680	65.5
Congenital anomalies	4,300,000	12,900	5.5
Chronic obstructive pulmonary diseases and allied conditions	20,500,000	70,140	29.7
Diabetes mellitus	35,600,000	35,900	5.2
Pneumonia and influenza	14,500,000	58,800	24.9
Total for weather-sensitive diseases	152,100,000	1,082,780	448.5
Total all causes	248,100,000	1,717,020	717.1

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[a] Conditions that can be influenced by changes in weather and climate are indicated in bold type.

Source: CDC (1986).

General Mortality and Illness

The relationship between mortality and weather has been studied for over a century with the (Kutschenreuter, 1959; Kalkstein, Vol. _) relationship between mortality and temperature receiving the most attention. Kutschenreuter (1959) observed "mortality is higher during cold winters and hot summers and lower during warm winters and cool summers." As indicated in Figure 14-2, the people most sensitive to temperature extremes are the elderly. Picciotto, 1985). One possible explanation is that for individuals already stressed by the circulatory problems associated with vascular and heart disease, heat waves "overload" the thermoregulatory system, which is struggling to maintain the appropriate body temperature. This results in heat stress, heatstroke, and often mortality as well (White and Hertz-Picciotto, 1985).

In addition to the elderly, people working in hot environments, such as steel mills and construction sites, are at special risk from heat waves (Dukes-Dobos, 1981). These workers face even greater risk if they have underlying medical problems such as the following:

- impaired circulation;
- lack of acclimatization/physical conditioning;
- higher than normal body temperature due to disease or exercise;
- chronic diseases such as alcoholism, diabetes, and obesity;
- reduced ability to sweat due to medications; and/or
- previous heat-related illness.

Cardiovascular, Cerebrovascular, and Respiratory Diseases

Although more information exists on the relationship of climate to total mortality from all causes, there is substantial information indicating that changes in climate variables are associated with impacts on the cardiovascular, cerebrovascular, and respiratory systems. As previously shown in Table 14-1, diseases or dysfunction of these three systems cause the majority of deaths observed on a yearly basis in the United States, as well as significant illness. Incidences of these diseases rise as climate extremes increase.

Changes in temperature may affect a number of heart problems including heart attack, coronary heart disease, and possibly coronary atherosclerosis and rheumatic heart disease (Vuori, 1987). Various stroke-related diseases are also thought to be

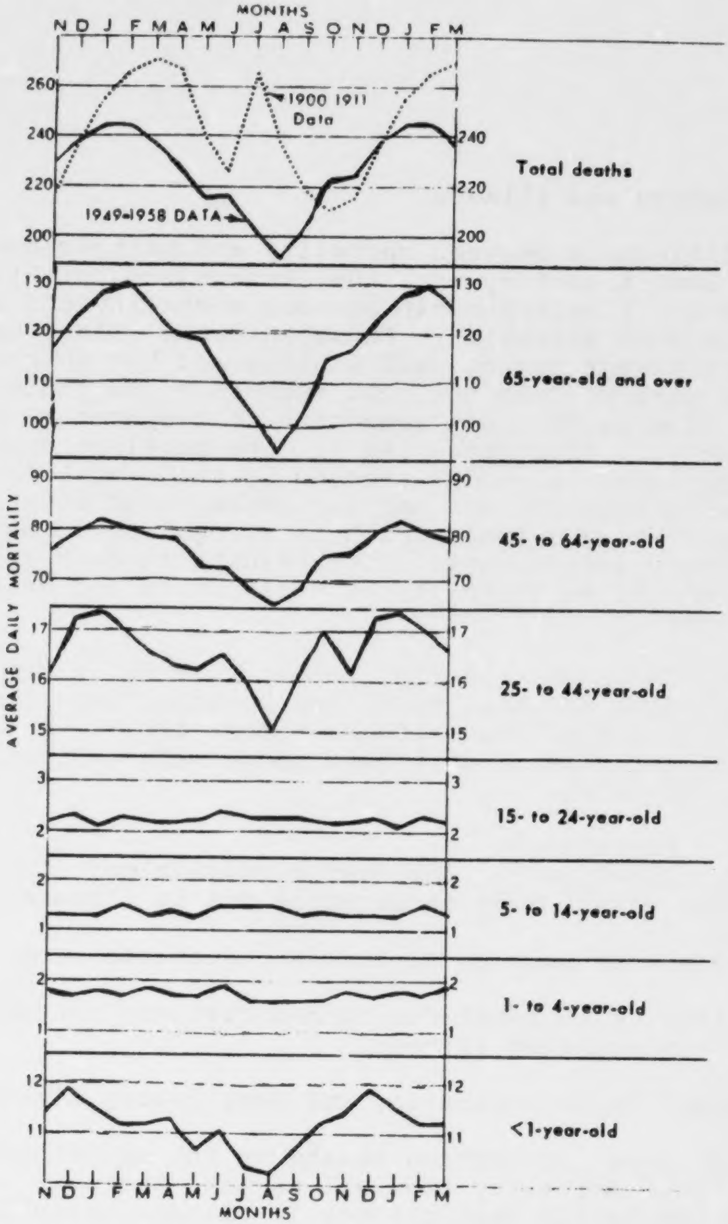

Figure 14-2. Annual Mortality for All Age Groups for 1949-58 a,b

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[a] Temperature curves are based on 1921-50 monthly normal temperatures.

[b] Mortality curves are based on daily average mortality for each month computed from 1949 to 1958 monthly totals of mortality reported for all age groups.

Source: Kutschenreuter (1959).

affected by weather (Gill et al., 1987). Respiratory diseases sensitive to weather include pneumonia, bronchitis, influenza and other respiratory virus infections, asthma, and hay fever. A number of respiratory ailments have been linked to air pollution, which varies seasonally because it is affected by changes in weather. Increases in the incidence of lung cancer, emphysema, chronic bronchitis, and asthma have been attributed to the presence of industrially and photochemically produced pollutants present in urban smog (Lopez and Salvaggio, 1983).

The exact relationship between temperature changes and illness from diseases such as heart attack and stroke is not as clear cut as the relationship reported for mortality from these diseases and temperature because mortality has national reporting procedures whereas illness has to be estimated from such data as hospital admission figures. In the few studies that have evaluated illness from cardiovascular or cerebrovascular disease, admissions have shown a relationship to weather changes similar to that observed for mortality (Sotaniemi et al., 1970; Gill et al., 1988).

Illness from respiratory diseases is somewhat easier to estimate, principally because two such diseases, asthma and hay fever, affect as much as 3 and 6% of the U.S. population, respectively, causing significant losses in work time. The most common seasonal pattern for the allergic type of asthma and for hay fever is an increased occurrence during the spring in response to grass pollens. A nonseasonal form of allergic asthma may also occur in response to allergens such as molds, which are affected by changes in precipitation and temperature.

Vector-Borne Diseases

Two tick-borne diseases currently posing a public health problem in the United States, Rocky Mountain spotted fever and Lyme disease, induce similar initial symptoms: high fever, chills, headache, backache, and profound fatigue. Rocky Mountain spotted fever can eventually result in hemorrhagic areas that ulcerate, and Lyme disease may cause permanent neurologic, cardiac, and rheumatologic abnormalities (APHA, 1985). The ticks that spread these diseases, and therefore the geographic distribution of the diseases themselves, are affected both directly and indirectly by climate variables. Such environmental factors as temperature, humidity, and vegetation directly affect tick populations and the hosts of the tick populations, e.g., deer, mice, and birds.

Mosquito-borne diseases, such as malaria and certain types of encephalitis (inflammation of the brain), are not a major health problem in the United States today because occurrences are relatively rare. However, mosquitoes are also weather-sensitive insects favoring a warm, humid climate. The spread of mosquito populations and the diseases they carry depends in part upon such climate factors as temperature, humidity, and upon vegetation, which is also influenced by the climate.

Human Reproduction

Preterm delivery (i.e., premature birth) and perinatal mortality (i.e., death just before, during, or just after birth) are two adverse reproductive outcomes that are associated with particular seasons and, thus, might be affected by climate change. Statistically significant increases in preterm births and in perinatal mortality in the summer months have been documented (Keller and Nugent, 1983; Copperstock and Wolfe, 1986) (see Figure 14-3). The data on total perinatal deaths correspond closely with those on perinatal deaths associated with infection in the mother or infant, suggesting that the seasonality in perinatal death observed is linked to a seasonality of reproductive infections (Keller and Nugent, 1983).

POTENTIAL HUMAN HEALTH EFFECTS OF CLIMATE CHANGE

To assess the effects of climate change on human health, EPA sponsored three studies for this report (Table 14-2). Wiseman and Longstreth (1988) reviewed the literature on the role of climate, season, and weather variables in the incidence of, and mortality due to, vector-borne diseases, and they evaluated the potential impact of climate change on these diseases in the United States. They also conducted a workshop of eminent scientists to evaluate the potential impacts of global climate change on vector-borne infectious diseases in the United States. Following the workshop, Haile (1988) conducted modeling studies of the potential impact of climate change on 1) the distribution of the American dog tick, vectors of Rocky Mountain spotted fever, and 2) the potential for malaria transmission in the United States. The third study, by Kalkstein (1988), was an extension of an earlier modeling study that assessed the potential effects of global climate change on the elderly and on total mortality in New York (Kalkstein et al., 1986). In Kalkstein (1988), the New York analysis was expanded to include 14 other cities. A detailed review of these three studies, supplemented with other information from the literature, is presented in this section.

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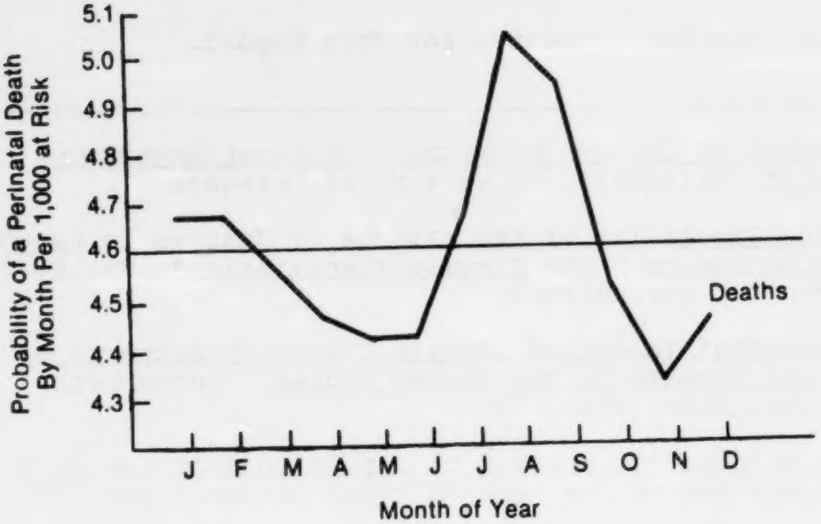

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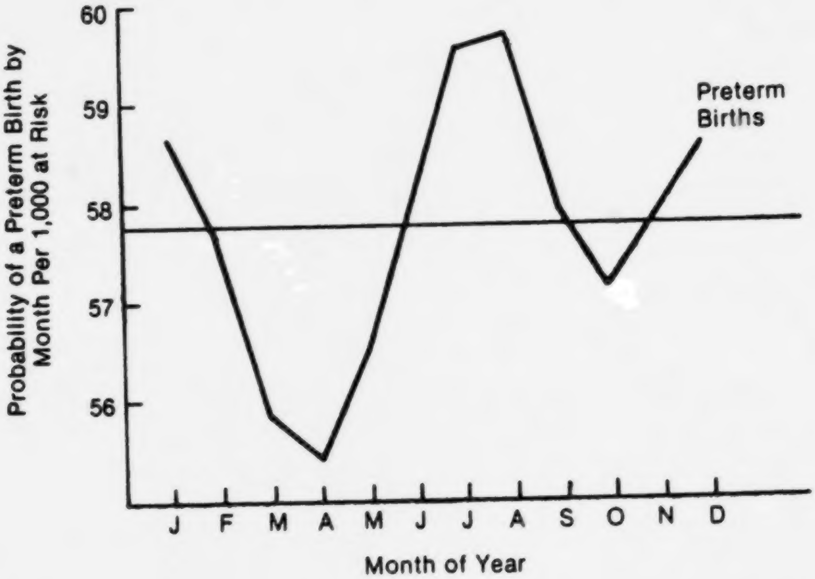

Figure 14-3. Probabilities of Perinatal Death [a] or Preterm Delivery [b]

Source: Keller and Nugent (1983).

Table 14-2. Studies Conducted for This Report.

- "The Impact of CO_2 and Trace Gas - Induced Upon Human Mortality" Kalkstein, University of Delaware.
- "Computer Simulation of the Effects of Changes in Weather Pattern on Veetor-Borne Disease Transmission" Haile, U.S. Department of Agriculture.
- "The Potential Impact of Climate Change on Patterns of Infectious Disease in the United States" Longstreth, ICF/Clement Associates, Inc.
- "Effect of Climatic Warming on Populations of the Horn Fly" Schmidtmann and Miller, Agricultural Research Service
- "Changing Animal Disease Patterns Induced by the Greenhouse Effect" Stenn, Mertz, Stryker and Huppi, Tufts University.

General Mortality

Preliminary analyses suggest that unless the U.S. population becomes fully acclimatized[*] to higher temperatures, climate change will be associated with a rising number of summer deaths. In addition, if climate change causes more intense heat waves, mortality is likely to increase. In the absence of complete acclimatization to warmer winters, the number of winter deaths is also likely to decline. With acclimatization, mortality may not decrease. It is not clear what the net effect of these two offsetting trends may be.

There have been very few studies of the effects of global climate change on human mortality. All of the identified effects have come from a single group of investigators: Kalkstein and his colleagues from the Center for Climate Research at the University of Delaware. This group (Kalkstein et al., 1986) developed a regression equation involving nine weather elements, such as temperature, windspeed, and humidity, to give the best algorithm for describing the current impact of weather on mortality. The algorithm used mortality data from New York City for 1964-66, 1972-78, and 1980.

The analysis revealed the existence of a summertime "threshold temperature" -- the maximum temperature above which mortality increases -- of 92°F for total deaths. This information was then used to assess the potential impact of climate change due to the emission of greenhouse gases, under the assumption that the population would not acclimatize, as well as under the assumption that it would acclimatize. Unacclimatized impacts were estimated by combining the climate scenarios and the historical weather algorithm described above, and acclimatized impacts were estimated by developing analogue cities that have weather variables today that look like those New York is estimated to have under climate change.

Under full acclimatization and a scenario predicting that New York will be 5 to 7°F warmer than it is today, no additional deaths were predicted. However, assuming no acclimatization, the number of summertime deaths attributable to temperatures above the threshold increased seven to ten-fold. Changes in winter weather were not estimated to affect mortality.

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[*] Estimations of the impact of warming on future mortality must address the question of whether humans will acclimatize (physiologically adapt) to changing weather. How quickly humans may become acclimatized is a topic of considerable controversy, so it is difficult to predict whether the climate changes being predicted will occur sufficiently slowly to allow acclimatization.

For this report, Kalkstein extended the New York analysis to cover 14 additional metropolitan areas and to evaluate the impact of two climate scenarios: the GISS doubled CO_2 scenario, and the GISS transient A scenario, evaluated at 30 years and at 60 years past the base period. Threshold temperatures were calculated for each city for summer and winter. Historical relationships between mortality and weather were derived independently for each of these 15 cities for both summer and winter. Table 14-3 summarizes the results for total mortality, by city and by season (summer or winter), for the doubled CO_2 scenario with and without acclimatization.

The cities with the highest estimated number of weather-associated summer deaths historically were New York City, Chicago, and Philadelphia: each averaged over 100 weather-induced deaths per summer. All of the cities with the highest average number of summer deaths are in the Midwest or Northeast, and those with the lowest number of summer deaths are in the South.

In the absence of any acclimatization, total summertime mortality in the United Stated under conditions of doubled CO_2 is estimated to rise from an estimated current total of 1,156 deaths to 7,402 deaths, with deaths in the elderly (aged 65 or over) subset contributing about 70% of each figure (727 and 4,605, respectively). Currently, the percentage of elderly in the U.S. population is increasing. Thus, the number of mortalities estimated to result from climate change may be larger than that found by Kalkstein because his analysis is predicated on today's age distribution. Even with full acclimatization, the number of weather-associated summer deaths approximately doubles to 2,198, possibly because hot weather increases physiological stress. Kalkstein's analysis also estimates a drop in the number of wintertime deaths. Historically, however, the number of weather-related deaths during the winter in the United States is much smaller (243) than that observed for the summer, and winter deaths were estimated to fall to 52 without acclimatization and to 159 with acclimatization. The net result for the United States is an increase in yearly mortality associated with doubled CO_2.

Table 14-3. Estimated Future Mortality Under Doubled CO_2 Climate Conditions Without and With Acclimatization

	Number of Deaths per Season					
	Summer			Winter		
City	Current	Without	With	Current	Without	With
Atlanta	18	159	0	2	2	0
Chicago	173	412	835	46	2	96
Cincinnati	42	226	116	14	6	0
Dallas	19	309	179	16	1	0
Detroit	118	592	0	16	2	37
Kansas City	31	60	138	21	5	0
Los Angeles	84	1,654	0	0	0	0
Memphis	20	177	0	0	0	0
Minneapolis	46	142	235	5	1	0
New Orleans	0	0	0	0	0	0
New York	320	1,743	23	56	18	25
Oklahoma City	0	0	47	0	0	0
Philadelphia	145	938	466	10	1	1
Saint Louis	113	744	0	47	7	0
San Francisco	27	246	159	10	7	0
Total	1,156	7,402	2,198	243	52	159

Source: Kalkstein (1988).

Cardiovascular, Cerebrovascular, and Respiratory Diseases

Overall global warming and climate change may exacerbate the effects of cardiovascular, cerebrovascular, and respiratory diseases. Data show an inverse relationship between mortality and temperature (i.e., deaths go down as temperature goes up) for the range between -5°C and about +25°C, with sharp increases at temperatures above and below this range, particularly for the elderly and for hot weather (White and Hertz-Picciotto, 1985).* Data illustrating this relationship for coronary heart disease and stroke are shown in Figures 14-4 and 14-5, respectively (Rogot and Padgett, 1976). This complex relationship precludes simple prediction of the net effect of climate change. For example, while it seems likely that hot weather-associated mortality from these diseases will increase in many localities, this trend is likely to be offset, at least in part, by a decrease in cold weather-associated mortality.

Just as higher summer temperatures are associated with increases in mortality from cardiovascular, cerebrovascular, and respiratory diseases, they are also likely to be associated with increases in the occurrence of these diseases. Particular stress may be put on the respiratory system because climate change can increase pollen, urban smog (discussed below), and heat stress.

For example, if, as has been suggested in the chapter on forests, climate change encourages a transition from forest to grassland in some areas, grass pollens could increase. This, in turn, may increase cases of pollen-induced hay fever and allergic asthma. (However, the switch from forest to grassland would reduce the amount of tree pollens that also cause allergic responses in some individuals.) Rises in humidity also may affect the incidence of mold-induced asthma and hay fever.

As indicated in the chapter on air pollution, global warming may modify global and regional air pollution because it is likely to be associated with changes in the concentrations of ozone and may also have impacts on acid deposition and general oxidant formation. Increasing occurrences of numerous respiratory diseases, such as lung cancer, emphysema, bronchitis, and asthma, have been attributed to the pollutants in urban smog (Lopez and Salvaggio, 1983). Many of the trace gases implicated in global warming contribute to these problems; other chemicals are created

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*The exact range appears to depend on the city.

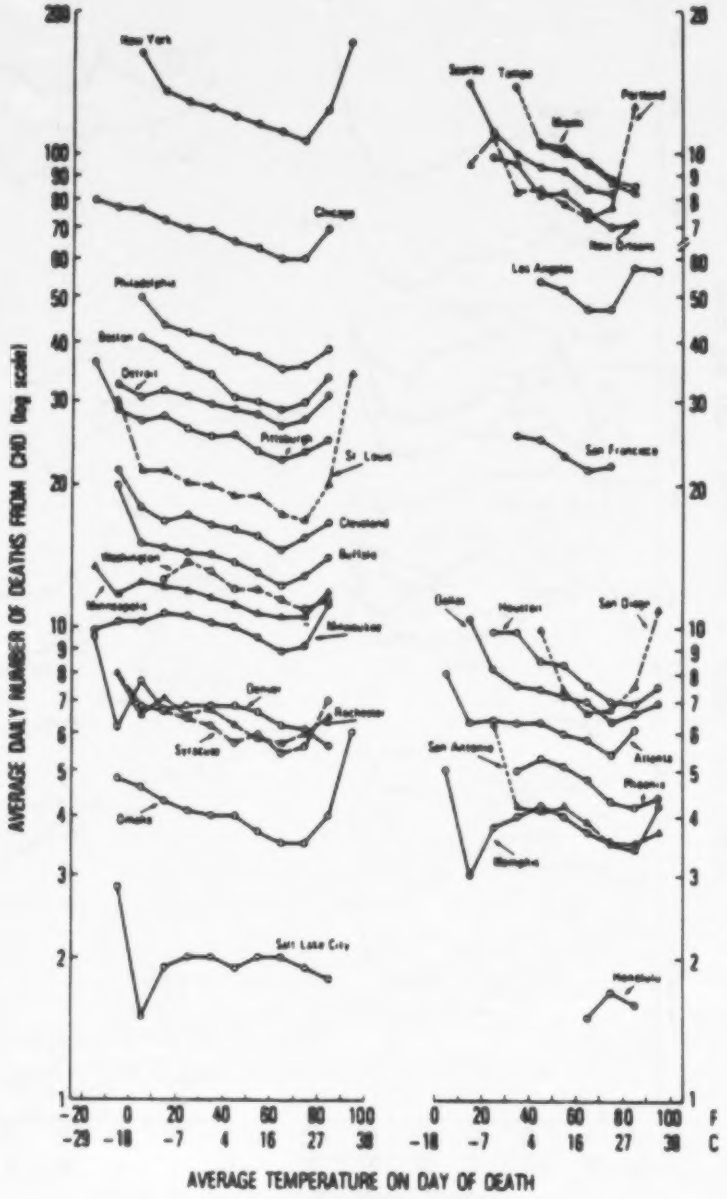


Figure 14-4. Relationship of Temperature to Heart Disease Mortality

Source: Rogot and Padgett (1976).

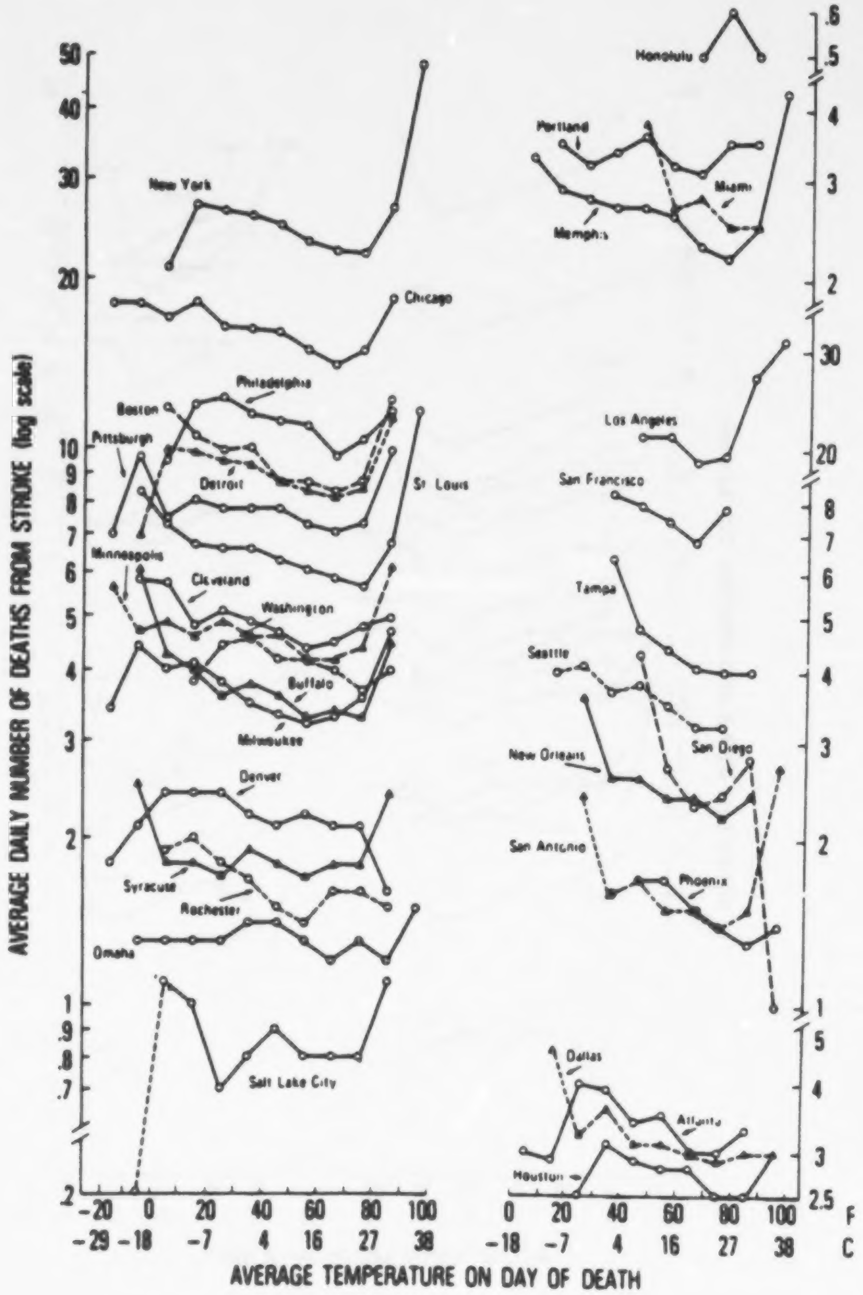


Figure 14-5. Relationship of Temperature to Mortality From Stroke

Source: Rogot and Padgett (1976).

from the interaction of ultraviolet light with these and other chemicals present in the atmosphere.

The component that causes the greates concern is urban smog (Grant, 1988). If global warming causes an increase in tropospheric ozone, serious consequences could result for adult asthmatics and people who suffer from acute or chronic bronchitis.

Vector-Borne Diseases

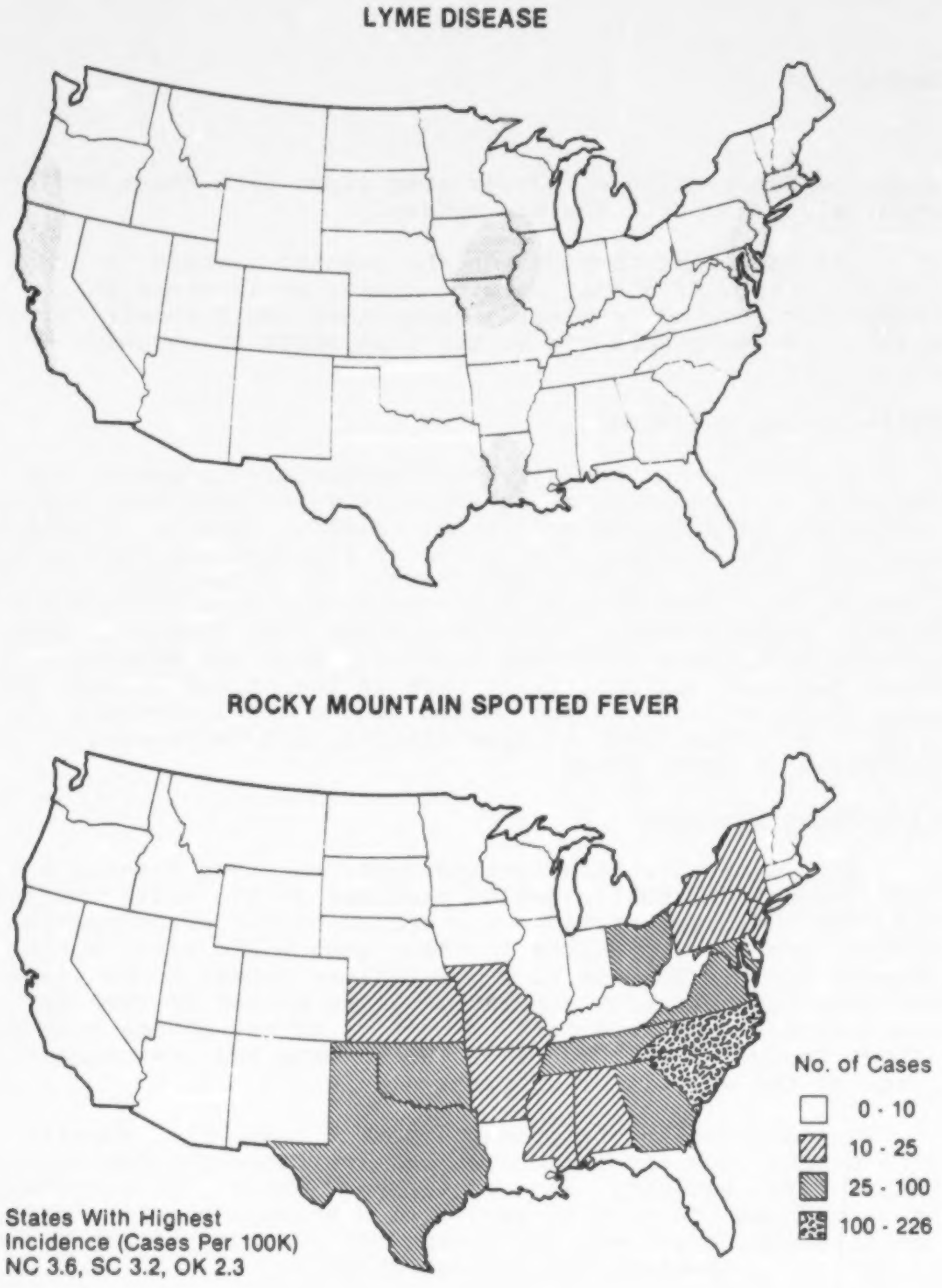
The changes in humidity and temperature caused by the increase in greenhouse gases are likely to alter the geographic ranges and life cycles of plants, animals, insects, bacteria, and viruses. (For further discussion of forestry and agriculture, see Chapter 11, Forestry, and Chapter 10, Agriculture.) For example, the range of many plant pests may move northward by several hundred miles. Such changes are also likely to occur for insects that spread diseases to both humans and animals. Vector-borne diseases are relatively rare in the United States, although most of those found in the United States are increasing in incidence. Some, such as Lyme disease, are increasing dramatically (CDC, 1986).

Tick-Borne Diseases

Both Rocky Mountain spotted fever and Lyme disease are considered to be public health problems in the United States. Although these two diseases are spread by different species of ticks, some overlap exists in their geographic distribution (Figure 14-6). Because tick populations appear to be limited by the size of their host populations, the spread of tick-borne diseases may be particularly sensitive to any change that may affect the geographic range of these hosts and, consequently, the range of the vector, or carrier.

In addition to the presence of the host, tick populations also depend upon the seasonality of environmental factors such as temperature, humidity, and vegetation. Optimally, climate must be warm enough to promote progression through the life cycles, humid enough to prevent the drying out of eggs, and cold enough in winter to initiate the resting stage.

As for many tick-borne diseases, the opportunity for a tick to acquire the infective agent from an infected animal is limited to the short period when the level of the agent in the blood of the host is high enough for the tick to receive an infective dose. Higher temperatures may increase the amount of the agent



LYME DISEASE

ROCKY MOUNTAIN SPOTTED FEVER

No. of Cases
☐ 0 - 10
▨ 10 - 25
▨ 25 - 100
▩ 100 - 226
States With Highest
Incidence (Cases Per 100K)
NC 3.6, SC 3.2, OK 2.3

Figure 14-6. Geographic Distribution of Lyme Disease and Rocky Mountain Spotted Fever

Source: Wiseman and Longstreth (1988).

(the organism that is transmitted by the carrier, such as a virus) and the time it remains lodged on the host animal. Both of these mechanisms will increase the rate of infection of the carrier. However, although higher temperatures may favor the presence of the agent, there is some indication that they could disrupt the life cycle of some tick species. In these cases, warmer temperatures would reduce both tick survival and the spread of diseases they carry.

Tick populations also vary with the natural vegetation of an area. The incidence of Rocky Mountain spotted fever, in particular, has been linked to natural vegetation and changes in climate.

In examining the potential impact of climate change in the United States on Rocky Mountain spotted fever, Haile used a weather-based model, ATSIM, to evaluate the impact of the scenario climate changes on the distribution of the American dog tick, the primary carrier of this disease (Haile, 1988; Mount and Haile, 1988). The model uses data inputs from the three GCMs to estimate population dynamics, growth rate, and generation time under the various scenarios. Haile assumed that habitats and host density did not change in response to global warming. Sample results for six cities representing the most southern, the most northern, and the two middle latitudes are presented in Figure 14-7. The results indicate that under all scenarios, tick populations would shift from south to north and would be virtually eliminated from the most southern locations (Jacksonville and San Antonio). However, in the middle latitude cities, the results are mixed and depend on the scenario evaluated.

In this analysis, the only model inputs that were changed to simulate climate change were the weather inputs. Other important parameters in the model are the distribution of habitat between forests and meadows and the presence of suitable hosts. Both parameters are likely to be changed relative to current conditions under climate change. As indicated in the chapter on forests, a change from forests to meadow may occur in certain areas of the country; this would depress the tick population. However, the distribution of small mammals also may change. If small mammal populations increased, tick populations would grow.

In a sensitivity analysis of their model, Mount and Haile (1988) found that the model predictions could vary sixteenfold, depending on the inputs used for host density, whereas the variability conferred by changes in the weather inputs is about fourfold. Based on the sensitivity analysis, host densities are

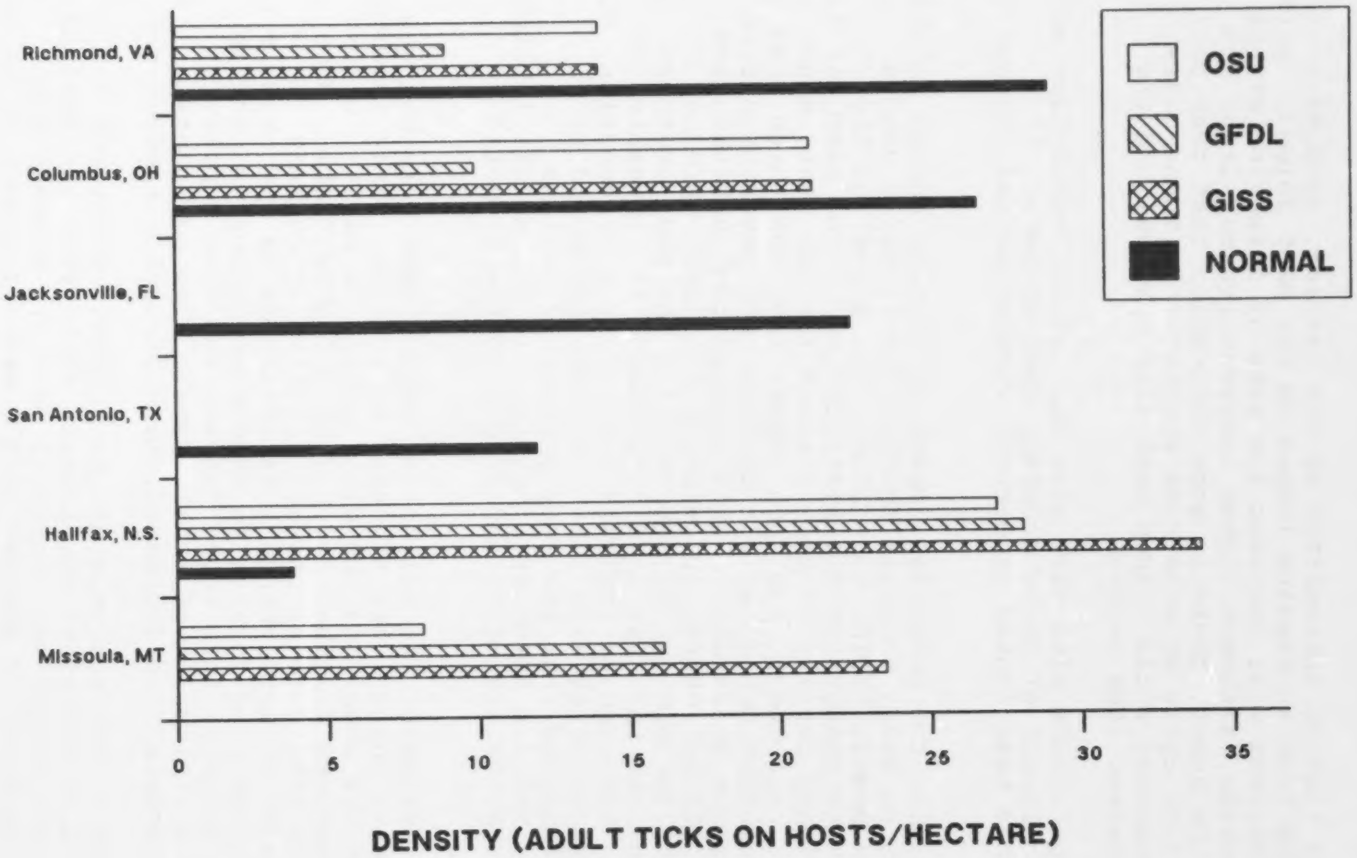


Figure 14-7. Simulated tick densities for selected cities under various scenarios of climate change.

Source: Haile. Volume __.

extremely important to these predictions. Keeping them constant, as was done in this analysis, could have underestimated the impact of climate change on the density of the American dog tick.

Mosquito-Borne Diseases

A second category of vector-borne diseases that can be affected by climate change consists of diseases carried by mosquitoes. Climate changes resulting in more days between 16 and 35°C, with humidity between 25 and 60%, are likely to favor the growth of mosquitoes (White and Hertz-Picciotto, 1985). Mosquito populations are also sensitive to the presence of standing water, which may or may not increase.

Worldwide, mosquito-borne diseases are associated with significant illness and mortality. In the United States, however, vector control programs and improved hygiene have virtually eliminated endogenously transmitted cases of these diseases, with the exception of sporadic outbreaks of arbovirus-encephalitis. (Imported cases are seen occasionally.) Numerous mosquito species are present in the United States, however. Recent restrictions on pesticide use, coupled with the influx of visitors and immigrants who can serve as sources of infectious agents, as well as the lack of available vaccines for many of the potential diseases, suggest the potential for reintroduction and establishment of these diseases in the United States -- particularly if global warming provides a more suitable climate for their growth and development (Wiseman and Longstreth, 1988).

Although there are numerous mosquito-borne diseases, at a recent workshop five were considered to pose a potential risk to U.S. populations if the status quo is disturbed by climate change (Wiseman and Longstreth, 1988). Malaria, dengue, and arbovirus-induced encephalitis were considered to be significant risks, and yellow fever and Rift Valley fever were considered to be possible risks.

Malaria

Malaria is an infectious disease transmitted by mosquitoes and induced by parasites (Plasmodia). The symptoms are highly variable, depending on the species of the agent. They include chills, sweats, and headache, and in severe cases, may progress to liver damage and even liver and renal failure.

Owing to effective vector control and treatment programs, malaria is no longer indigenous to the United States. However, imported cases occur regularly, and occasionally indigenous transmission has been documented (Wiseman and Longstreth, 1988). Current demographic trends in the United States, including a large number of legal and illegal immigrants from locations where malaria is endemic, could result in the presence of a sufficient pool of infected individuals that in conjunction with climate changes may create sufficiently favorable conditions for increased incidence of the disease.

Haile used the weather-dependent model MALSIM to evaluate the potential impact of climate change on malaria in an infected population living in an area where a competent carrier is present. The MALSIM model showed that several cities in the South (e.g., Miami, Key West, and Orlando) under current climate conditions are very favorable for malaria transmission. In general, however, very little change was estimated for the transmission potential of malaria in the United States (Figure 14-8). In a few cities, e.g., Richmond, Nashville, and Atlanta, the model estimated large increases in one scenario relative to those that would occur normally. However, the results varied with different climate scenarios and did not occur at all locations.

Dengue Fever

Dengue fever is an arbovirus-induced* illness characterized by fever, rash, and severe pain in the joints. Like malaria, it is not currently endemic in the United States, although potential carriers are present (see Figure 14-9) and the disease is imported here regularly by people who have traveled abroad.

The first infection by the virus generally is not fatal. However, a second infection, particularly by a type of virus different from the first, can result in much more serious forms of the disease that can be fatal, particularly in the very young and the elderly.

The ability of the vector to transmit the agent appears to depend on temperature, and current conditions do not appear to be favorable for this process. Climate changes that raise temperatures, however, may reduce the required incubation period

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*An arbovirus is a virus transmitted by an arthropod. Arthropods are a group of animals that include insects and crustaceans. Examples of arthropods that transmit disease include mosquitoes and ticks.

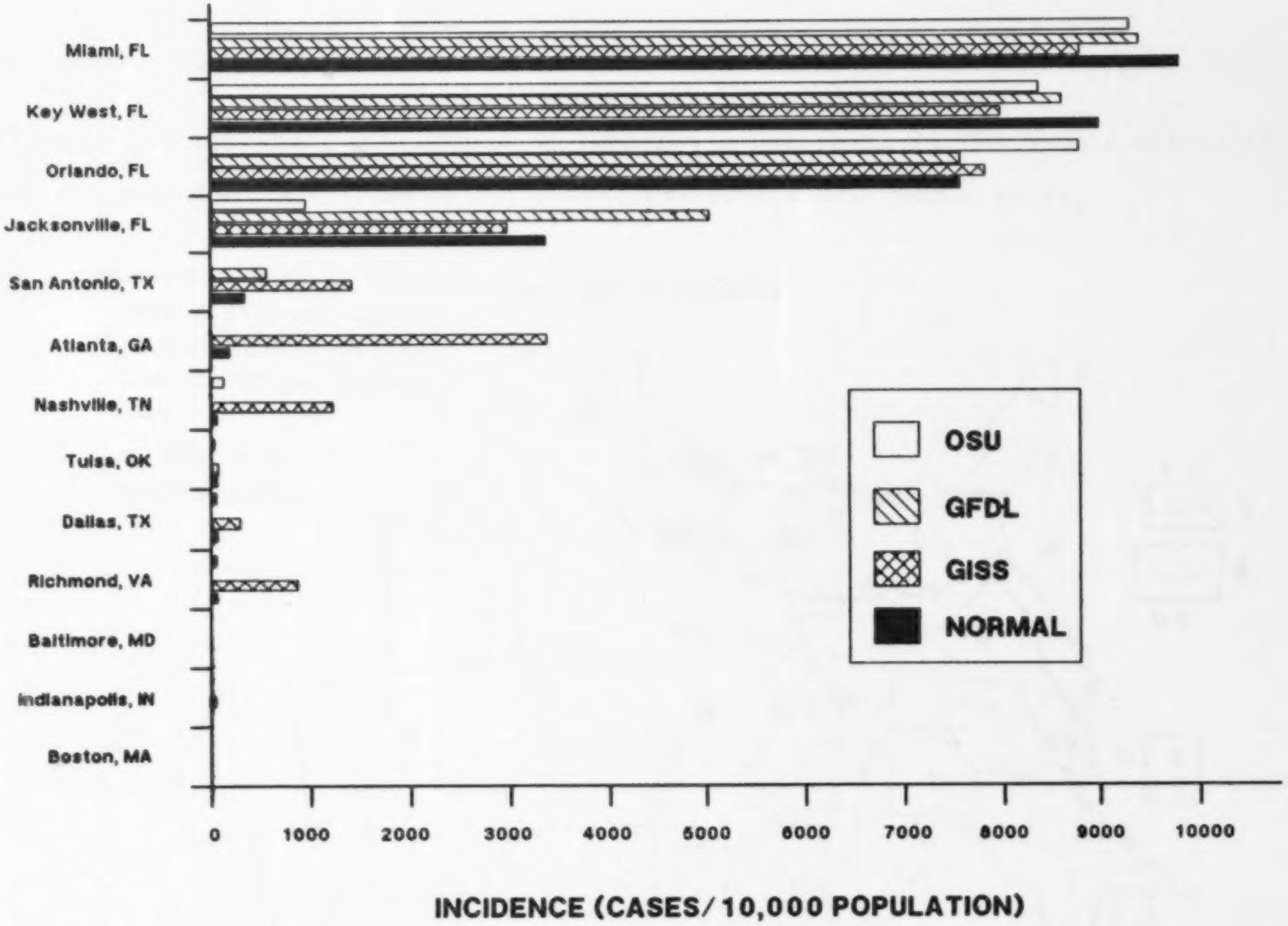
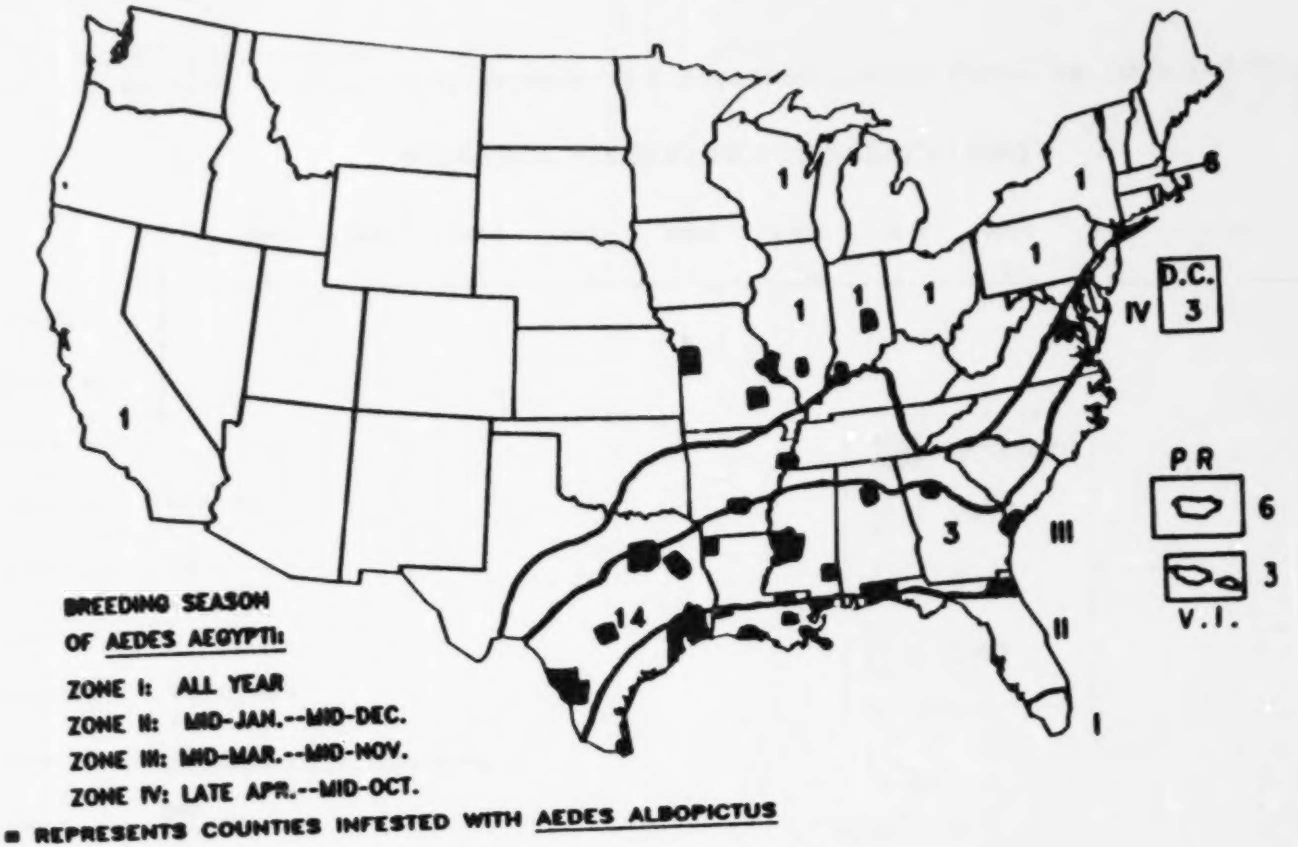


Figure 14-8. Simulated incidence of malaria for selected cities under various scenarios of climate change.

Source: Haile. Volume __.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V.I.
BREEDING SEASON
OF AEDES AEGYPTI:
ZONE I: ALL YEAR
ZONE II: MID-JAN.--MID-DEC.
ZONE III: MID-MAR.--MID-NOV.
ZONE IV: LATE APR.--MID-OCT.
■ REPRESENTS COUNTIES INFESTED WITH AEDES ALBOPICTUS

Figure 9. Geographic distribution of mosquitoes that carry dengue fever[a]

[a] Arabic numerals represent the number of imported cases found in the United States in 1984.

Source: Grant (1988).

and increase the infectivity of the carrier, increasing the potential transmission of the disease.

Arbovirus-Related Encephalitides

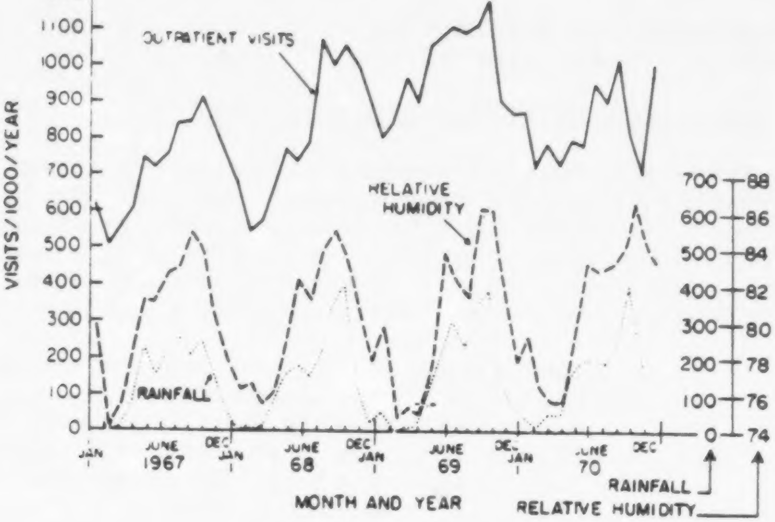
Arbovirus-related encephalitides are a group of acute inflammatory diseases that involve parts of the brain, spinal cord, and meninges. In mild cases, these infections result in feverish headaches or aseptic meningitis; in more severe cases, those symptoms can be accompanied by stupor, coma, convulsions (in infants), and occasionally spastic paralysis (APHA, 1985).

At least eight types of viruses causing encephalitis are present in the United States. Cases range in severity depending on the type of virus, with yearly fatality rates between 0.3 and 60%, These infections are rare. In 1984, 129 cases were reported to the Centers for Disease Control, which maintains an active surveillance program for them (CDC, 1986).

Outbreaks of encephalitis attributable to these viruses are normally limited to specific geographic locations and seasons for several reasons. First, summer temperatures are normally required for the viruses to multiply and to be transmitted to a new host. Increased temperatures may quicken the transmission process and promote epidemic disease. However, the extent of this effect depends largely on the particular virus. Some viruses require cooler weather and higher moisture conditions. Thus, higher temperatures may reduce their prevalence. Second, environmental conditions that favor the presence of carriers and hosts must prevail. For example, relative humidity may affect plant life necessary for the feeding of hosts.

Other Diseases

A variety of other U.S. diseases indicate a sensitivity to changes in weather. Higher humidity may increase the incidence and severity of fungal skin diseases (such as ringworm and athlete's foot), and yeast infections (candidiasis). Studies on soldiers stationed in Vietnam during the war indicated that outpatient visits for skin diseases (the largest single cause of outpatient visits) were directly correlated to increases in humidity, but showed a 4-month lag with relationship to temperature increases (Figure 14-10). In addition, excessively high temperatures can lead to such skin diseases as prickly heat and heat rash, which impair the ability of the skin to breathe and thus place additional stress on people already suffering from overexposure to heat from other causes.



Outpatient visits for skin diseases in relation to mean monthly temperature index: U.S. Army personnel in Vietnam, 1967–70

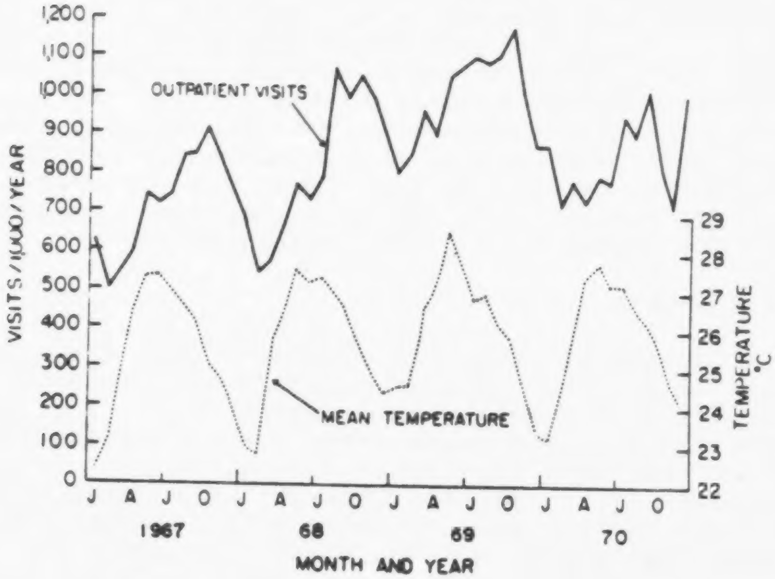


Figure 14-10. Relationship of Skin Infections to Humidity and Temperature.

Source: Longstreth and Wiseman, Volume __.

Several diseases appear to be associated with the acquisition of winter infections. If a reduction in winter severity is also accompanied by a decrease in wintertime infections, these diseases could be reduced under global warming.

For example, birth in cold winter months has been associated with a higher risk of schizophrenia in individuals whose schizophrenia is without an apparent genetic component (Kovelman and Scheibel, 1983). In addition, juvenile-onset diabetes, which has been reported to be increasing over the past several decades, has been shown to be associated with a seasonal variation in that the month of first admission peaks in the winter (Glatthaar et al., 1988; Patterson et al., 1988). It is a common clinical experience that a minor viral illness precedes the onset of symptoms.

NATIONAL IMPLICATIONS

Human societies possess considerable ability to adapt to change. The potential for climate to affect human health may be considerably modified by adaptive responses, such as immunizations, modification of the environmental temperature (e.g., use of air conditioners), and control of disease carriers.

In addition, several demographic and technological trends (the aging of the population, an influx of immigrants, advances in treatment techniques) make it difficult to analyze the potential impacts of climate change on human health. Although this chapter attempts to identify those human health effects at risk from climate change, the analyses were not designed to consider adaptive responses and should not be treated as absolute predictions of what will happen with climate change. Rather, the analyses presented here represent possible scenarios in the absence of consideration of demographic trends or adaptive responses that may either exacerbate or ameliorate the impact of climate change on human health.

Climate change may affect regional and national health care. For instance, the treatment requirements for asthma may increase or decrease as locations experience changes in the distribution and intensity of pollen concentrations. Increased resources may be needed to treat premature infants if there is an increase in the number of preterm births. If heart attacks, stroke, and respiratory problems increase, hospitalization costs and costs due to days lost from work may also increase. Higher health care costs might be particularly obvious in Medicaid and Medicare because those below the poverty line would be less able to take adaptive measures (e.g., air-conditioning), and the elderly are more susceptible to the ill effects of extreme weather conditions.

The United States is already dealing with an infant mortality problem higher than that of any other industrialized nation (World Bank, 1987). Infant mortality is higher in the summer; consequently, the increased temperatures expected with global warming may well exacerbate the problem.

The need for irrigation may increase in many regions of the U.S. (see Chapter 10, Agriculture). Irrigation may result in greater amounts of standing water and can therefore increase mosquito populations. Arbovirus encephalitis may become a greater problem than at present, and other mosquito-borne diseases, such as dengue or yellow fever, could be more easily spread if introduced.

POLICY IMPLICATIONS

The full impacts of climate change on human health will require more research. Agencies such as the Department of Health and Human Services should consider conducting studies a potential impact.

In the future a cadre of trained professionals may be needed to respond to outbreaks of diseases. A shift in the distribution of carriers of human disease may necessitate regional shifts in surveillance and eradication programs. States that do not have these programs may need to develop them in the future.

RESEARCH NEEDS

One of the largest potential impacts of climate change apparent in the literature is the increase in perinatal mortality and preterm births. An analysis similar to that performed by Kalkstein, but focusing strictly on deaths in the 0- to 1-year age group, might be warranted. In addition, some refinements to the Kalkstein analysis -- e.g., focusing on the distinct causes of death, and a more detailed analysis of the analogue modeling results -- are needed to provide additional insight into the robustness of the conclusions from that study.

The modeling that has been performed for vector-borne diseases did not assess the potential impact of changes in the host population (or habitat) that might result from climate change. Additional analyses are needed that evaluate what the changes in host populations and habitat are likely to be and how those changes could affect predictions from the ATSIM and MALSIM models.

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DRAFT

CHAPTER 15

URBAN INFRASTRUCTURE

FINDINGS

Global climate change could require U.S. cities to make major changes in capital investments and operating budgets. Areas most likely to be affected include water supplies, roads, and bridges, storm sewers and flood control levees, and energy demand in municipal buildings and schools.

- Most urban infrastructure in the United States will turn over in the next 35 to 50 years. If changes in climate are considered, this turnover will allow cities to prepare for climate change at lower costs. In some cases, the risk of climate change should be incorporated into decisions beginning today, such as coastal drainage systems that are likely to last for 50 to 100 years.

Northern Cities

- Northern cities, such as Cleveland, may incur a change in the mix of their expenditures. In such locations, increased electricity costs for air conditioning could be offset by reductions in expenditures for heating fuel, snow and ice control, and road maintenance. Southern cities could see increases in operating budgets due to the demand for additional air conditioning.

Coastal Cities

- Coastal cities may be subject to more severe impacts. These include 12 of the 20 largest metropolitan areas. For example:
    - Sea level rise or more frequent droughts would increase the salinity of shallow coastal aquifers and tidal surface waters. Cities that rely on water from these sources need to examine water supply options. Such areas as Dade County, Florida, or New York City will probably be vulnerable.
    - As sea level rises, some coastal cities would require levees to hold back the sea or fill to raise the land surface area. In the case of Miami, the cost of these activities might be more than $500 million over the next 50 to 75 years.

Water Supply and Demand

- Climate change will influence the supply and demand for water in many cities. A lengthened summer season and higher temperatures will increase the use of water for air conditioners and lawns and gardens. Changes in rainfall patterns, runoff, and flood control measures may alter water supplies. In the Hudson River Basin, summer water demand could increase by 5 percent over the demand for water without climate change, while supplies might fall. Such a change would require new institutional and management approaches for both the Delaware and Hudson Rivers.

Policy Implications

- Climate change has implications for many national programs and policies. For example:
  - The National Flood Insurance Program may react to climate change by redrawing flood plain maps and adjusting insurance rates to account for sea level rise and changes in river flows. It may be prudent to examine whether this program should anticipate climate change by discouraging development that would be vulnerable in the future.
  - Because of the key role federal programs play in the development of cities, the Department of Housing and Urban Development should examine the implications of climate change on long-term policies. A minimum response might be to provide guidance on the certainties and uncertainties of climate change to groups such as the National League of Cities, the U.S. Conference of Mayors, and the American Planning Association.
  - Because water supply infrastructure may last for several centuries, improved planning is important. The U.S. Geological Survey should study the probable impacts of global climate change and sea level rise on the water supplies of major cities. The Corps of Engineers should factor climate change into the design of major projects.
  - Given the assumption that modest changes in the design and location of many transportation systems may facilitate an accommodation to climate change, the Department of Transportation should factor climate

change into the design of roads, bridges, and mass transit facilities.

-- Voluntary standard organizations, such as the American Society of Civil Engineers, the Building Officials and Code Administrators, International and American Society of Heating and Refrigerating and Air Conditioning Engineers should examine the need for changes in existing standards to improve the use of energy and safety factors.

RELATIONSHIP BETWEEN URBAN INFRASTRUCTURE AND CLIMATE

Three-quarters of the U.S. population is concentrated in urban areas (Statistical Abstract, 1987). The majority of the nation's investment in water supply, wastewater transport and treatment facilities, drainage, roadways, airports, mass transit, electric power, solid waste disposal sites, and public buildings serves these urban areas. The current value of selected infrastructure nationwide, displayed in Table 15-1, provides insight into the aggregate investment at stake if climate changes. Most of these items could be considered part of urban infrastructure, and have been located and designed based on historic meteorologic information.

Eighteen of the 20 most populated U.S. cities have access to oceans, major lakes, or rivers* and have invested in additional infrastructure for port facilities and flood control. The expenditure required to construct coastal defense structures -- which prevent inundation by the sea, slow oceanfront erosion, control storm surges, slow saltwater advance up rivers, and reduce saltwater intrusion into aquifers -- is now minimal.

Although actual practice varies, the nominal replacement cycle for most infrastructure is 35 to 50 years (National Council on Public Works Improvement, 1988). Some water supply investments have 100-year cycles. Between planned replacement

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*Of the 20 most populous cities in the U.S., twelve are tidal waterfront cities (Baltimore, Boston, Houston, Los Angeles, Miami, New York, Philadelphia/Wilmington, San Francisco/Oakland, San Diego, Seattle, Tampa/St. Petersburg, and Washington, D.C.), three are located on the Great Lakes (Chicago, Cleveland, and Detroit), three are on navigable rivers (Minneapolis, Pittsburgh, and St. Louis), and two are not on a navigable waterway (Atlanta and Dallas).

TABLE 15-1. Value of the Nation's Stock of Selected Infrastructure (Billions of 1984 Dollars)

Component	Value[a]
Water supply	$108
Wastewater	136
Urban drainage	60
Streets	470
Public airports	31
Mass transit	34
Electric power (private only)[b]	266
Public buildings	unknown
Total	$1,107+

[a] Based on a useful life of 35 to 50 years for most assets, and 10 to 20 years for transit vehicles.

[b] About 77% of electric power is privately produced.

Source: Statistical Abstract (1987); National Council on Public Works Improvement (1988).

cycles; however, sea level rise, temperature change, and changes in precipitation patterns all could alter the balance between water supply and demand. The nature and pattern of precipitation could affect drainage requirements as well as highway design and maintenance.

The heat wave of 1988 vividly illustrated some of the potential impacts. Hundred-degree weather distorted railroad tracks, forcing Amtrack to cut speeds from 200 to 128 km per hour between Washington and Philadelphia (Bruske, 1988) and possibly causing a train wreck that injured 160 people on a Chicago-Seattle run (The Washington Post, 1988). A U.S. Army Corps of Engineers contractor worked around the clock for 2 weeks to build a 170-m-wide, 9-m-high silt wall across the bottom 40% of the Mississippi River channel, 48 km below New Orleans (Sossaman, 1988a,b). This $2 million wall, designed to wash away when spring snow melt demands the full capacity of the channel, slowed an advancing wedge of saltwater that threatened the water supply in New Orleans and nearby parishes. In Manhattan, heat exacerbated the effects of long-standing leaks in 256 km of steam pipes, causing the asphalt to soften. As vehicles kneaded the soft asphalt, thousands of bumps formed on city streets, requiring extensive repairs (Hirsch, 1988). In the suburbs of Washington, D.C., steel expansion joints bubbled along a 21-km stretch of Interstate 66 (Lewis, 1988).

This chapter will examine such issues as the portions of the infrastructure that will be significantly affected, and anticipated costs and who will bear them.

PREVIOUS CLIMATE CHANGE STUDIES ON URBAN INFRASTRUCTURE

Available literature on the potential effects of global climate change on urban infrastructure is sparse. Rhoads et al. (1987) examined the potential impacts of sea level rise on water supply and flood protection in Dade and Broward Counties, Florida, and concluded that the effects might be severe. Hull and Titus (1986) analyzed the potential impact of sea level rise on water supply in the Philadelphia-Wilmington-Trenton area, and found that a rise of 0.3 m could require adding 140 million m^3 of reservoir capacity, about a 12% increase, to prevent saltwater from advancing past water intakes on the Delaware River. Additional investment would be required to prevent or respond to saltwater infiltration into underground aquifers.

Two recent studies illustrate the importance of considering sea level rise in urban coastal infrastructure planning and the uncertain nature of the decisions involved. Wilcoxen (1986) examined the impact of sea level rise on a portion of San Francisco's sewage transport system that is buried close to the shoreline. The study estimated that if sea level rose 0.6 m by the year 2100, an expenditure of roughly $70 million on beach nourishment might be required to prevent damage to a structure that cost $100 million to build in the late 1970s. The author suggested that consideration (at no additional cost) of sea level rise in siting the structure could have prevented these expenses. Titus et al. (1987) examined the impact of sea level rise on a proposed coastal drainage system in Charleston, South Carolina, and estimated that a 0.3-m sea level rise by 2025 would require almost $2.5 million in additional investments to maintain the target level of flood protection. The present value of these investments is $730,000. In contrast, only about $260,000, one-third of the cost of responding in 2025, would be required to add this level of protection at initial construction.

URBAN INFRASTRUCTURE STUDIES IN THIS REPORT

Several studies undertaken for this report examined some of the implications of climate change in relationship to urban infrastructure. One study comprehensively examined the impacts on infrastructure in several cities:

- Impact of Global Climate Change on Urban Infrastructure (Walker et al., The Urban Institute)

The following studies, referenced in this chapter, covered issues relating to urban infrastructure:

- Electric Utilities (Linder et al., 1987)
- The Impacts of Low Lake Levels on the Illinois Shoreline (Changnon, year)
- Case Studies of the Water Supply Systems of California and Atlanta, Georgia (Sheer, year)
- Defending Unprotected Shorelines (Leatherman, year)
- Defending Protected Shorelines (Weggel, year)

RESULTS OF THE INFRASTRUCTURE STUDIES

Impacts on Miami, Cleveland, and New York City

Walber et al. examined three cities distinctly affected by climate change to determine a range of impacts on urban infrastructure.

Study Design

The study was based on a critical review of existing infrastructure studies in the three cities, discussions of likely impacts with local infrastructure experts, analyses undertaken by these experts, and preliminary calculations of probable impacts. Experts were presented with GCM scenarios for CO_2 doubling, and scenarios were used to calculate effects on energy demand, roadways, and other systems. The study also derived conclusions based on experiences in other cities where current temperatures are analogous to temperatures projected for the cities under study, using the analogues identified by Kalkstein (Vol.).

Limitations

The principal limitation of the overall study is the limited use of hydrologic and other modeling. In addition, experts were asked to derive conclusions regarding conditions beyond their experience. Since only three cities are included, the full range of effects on urban infrastructure was not covered. The authors did not perform engineering analyses of cost-effective responses, and they did not assess the potential for reducing impacts through technological change.

Results and Implications

Miami's Infrastructure

Greater Miami is bounded by water on all sides during the rainy season. An extensive network of canals and levees has been built to control ocean and freshwater flooding and to recharge the aquifer beneath the area. Miami has one of the world's most porous aquifers, which lies less than 1.5 m below the surface in one-third of the developed area. Federal law requires that roughly 15% of Miami's freshwater be released into the Everglades National Park. The Dade County Development Master Plan predicts that by 2000, a water supply deficit will force use of desalinated water at three times current water costs.

The Miami case study examined the probable impacts of climate change and sea level rise on Dade County's water supply, water control and drainage systems, building foundations, roads, bridges, airports, solid waste disposal sites, and sewage transport and treatment systems, assuming that a gradual sea level rise would be managed through strategies such as raising the land in low-lying areas, upgrading levees and dikes with pumped outflows, retreat selectively from some areas, and increasing the freshwater head roughly in proportion to sea level rise to prevent saltwater infiltration into the aquifer.

As Table 15-2 shows, global climate change could require $500 million ($ ½ billion), in capital investment in Greater Miami over the next century. Because many systems could not be estimated and because a complete engineering analysis was not performed, these results should only be considered as rough estimates.

The south Florida aquifer is currently under pressure because of growth in the Miami area. Because the aquifer extends under the ocean, the typical urban response to a rising sea -- diking the water at the surface and pumping out the seepage from

TABLE 15-2. Probable Infrastructure Needs and Investment in Miami in Response to a Doubling of CO_2 (Millions of 1987 Dollars)

Infrastructure Need	Cost
Raising canals/levees	$60
Canal control structures	$50
Pumping	not estimated
Raising streets	$250 added to reconstruction cost
Raising yards and houses	not estimated
Pumped sewer connections	not estimated
Raising lots at reconstruction	not estimated
Drainage	$200-300
Airport	$30
Raising bridges	not estimated
Sewer pipe corrosion	not estimated
Water supply	more use of desalinated water at double
present	water prices

Source: Walker et al, Volume __.

ditches behind the dikes -- appears to be unworkable. Unless the dike extended down more than 45 m, rising seawater pressure would cause the sea to rush into the aquifer below the surface and push freshwater upward, almost to the surface.

The one-time capital costs for upgrading existing canals and levees in response to a 1-m sea level rise would be about $12 million. However, almost $50 million in new control structures, including extensive pumping capacity, might be required for the canals used to maintain the freshwater head. Large-scale pumping for canvas also could involve substantial operating costs, but these have not been estimated. Storm sewers and drainage would cycles; however, sea level rise, temperature change, and changes in precipitation patterns all could alter the balance between water supply and demand. The nature and pattern of precipitation need upgrading, requiring investment of several hundred million dollars above normal replacement costs.

Building foundations generally should remain stable if the freshwater head rises 1 m because houses are built on concrete slabs, most buildings in newer areas already are built on raised lots to meet Dade County's flood control ordinance, and the foundations of many larger buildings already extend into the water table.

Conversely, the water table could infiltrate the base of about a third of Dade County streets, which would have to be raised or risk collapse. If sea level rose gradually, thereby permitting raising of streets and related sewer mains during scheduled reconstruction, the added public cost might be approximately $250 million. Building owners would incur substantial costs to improve drainage, raise yards, raise lots at reconstruction, and pump sewage to mains. Miami's airport also would need better drainage, requiring an approximate $30 million investment.

A 1-m rise in sea level would require raising most bridges to ensure adequate clearances and reduce vulnerability to storm surges during hurricanes.

Global climate change could force Dade County to greatly expand its planned use of desalinated water. This may also be needed by the Everglades National Park, if it is protected from the rising sea.

Analysis of Miami's coastal defense and water supply options provides insight into the likely impacts of sea level rise on cities built on coral reefs, but not into the likely response of most mainland cities on the U.S. coastline. Dade County is unusual because readily extracted fill is extensively available on public lands having easy access to a canal system that can be navigated by flat-bottomed barges. Nevertheless, this case study suggests that global climate change could force large coastal cities to invest billions of dollars to add and upgrade infrastructure.

Cleveland's Infrastructure

The Cleveland case study examined impacts of climate change on snow and ice control costs, road construction and maintenance, heating and cooling costs and equipment needs, water supply, and storm and wastewater transport. The study also includes a preliminary analysis of the effects of a drop in the level of Lake Erie as estimated by Croley (see Great Lakes chapter of this report). The impact on the snow and ice control budget was estimated by analogy to the budget in Nashville, Tennessee.

Results are displayed in Table 15-3, which shows that the net impact of climate change on Cleveland's annual infrastructure costs could be negligible, although expenditures probably would shift between categories. In addition to the costs shown in Table 15-3, a one-time capital expenditure of \$68-80 million could be required to add air-conditioners in public buildings. Also, many private residences probably would install air-conditioners.

Walker et al. estimated that global climate change could cause annual snowfall in Cleveland to drop from 1.25 to roughly 0.2 m, reducing annual snow and ice control costs by about \$4.5 million. Decreased frost damage to roads and bridges could yield further savings estimated at \$700,000 per year. An estimated drop of \$2.3 million per year in heating costs for public buildings also was projected. Conversely, annual public air-conditioning costs seemed likely to rise by \$6.6-9.3 million. The impacts on the transit operating budget seemed likely to mirror the impacts on the general budget, with reduced mishaps and traffic delays in ice and snow offsetting increased fuel costs for vehicle cooling.

The study suggested Cleveland might spend about \$65-80 million to add air-conditioning to older schools and large nonoffice spaces such as gyms and repair garages. Much of this expenditure would occur as buildings were replaced or refurbished and might have occurred even without climate change.

The rise in winter temperatures associated with a doubling of CO_2 might allow Cleveland to use thinner pavement resulting in possible savings of about 3% in road resurfacing costs and 1% in reconstruction costs. The net savings could average about \$200,000 per year or 1.3% of the city's current capital budget. Standard engineering estimates (AASHTO, 1987) suggested that the rate of pavement deterioration probably also should decline as winter temperatures rise, saving roughly \$500,000 per year.

A climate-induced drop in the level of Lake Erie probably would not adversely affect Cleveland, although some dredging might be required in the Cuyahoga River. Upgrading of the city's combined storm and wastewater collection system appeared to be unnecessary, although this would depend upon rainfall variability.

TABLE 15-3. Estimated Impacts of a Doubling of CO_2 on Cleveland's Annual Infrastructure Costs (Millions of 1987 Dollars)

Cost Category	Annual Operating Costs
Heating	-$2.3
Air-conditioning	+$6.6-9.3
Snow and ice control	-$4.5
Frost damage to roads	-$0.7
Road maintenance	-$0.5
Road reconstruction	-$0.2
Mass transit	summer increase offsets winter savings
River dredging	less than $0.5
Water supply	negligible
Storm water system	negligible
Total	-$1.6 to +$1.1

Source: Walker et al. (Volume __); Weggel et al. (Volume).

If temperature rises several degrees, most northern cities probably could anticipate savings in snow and ice control, heating, and roadway construction and maintenance costs similar to those described for Cleveland. These savings might approximately offset the increase in air-conditioning costs. Communities south of Cleveland probably would experience modest budget increases. Cleveland could become a more attractive location for water-intensive industry if water supplies in other areas become less reliable. Resulting in-migration could bring further growth-related infrastructure costs. (See Great Lakes chapter for a further discussion of this issue.)

New York City's Water Supply

New York City's infrastructure may be affected in many ways by global climate change. Temperature change could affect the same capital expense categories in both New York City and Cleveland. In addition, the city may have to invest heavily to protect underground infrastructure from seawater infiltration.

The most pressing, and perhaps largest, problem facing the city may be the effects of global climate change on the adequacy of the city's water supply. The New York City study focused on that issue.

The New York metropolitan area draws water from the adjoining Hudson and Delaware River Basins and from underground aquifers serving coastal New Jersey and Long Island. Figure 15-1 shows the region and its water supply sources.

The water supply network is in deficit. The Mayor's Task Force (1987) has recommended remedying New York City's portion of the deficit through better management of water demand and detailed study of the possibility of reactivation of a water intake at Chelsea, a $223-391 million investment that would yield 375 to 750 million liters of water daily.

Walker et al. estimated changes in water demand using design standards for commercial cooling-tower demand, changes in electricity demand estimated by Linder et al. (1987), historic residential summer water use, and estimates by Hull and Titus (1986) of saltwater advance up the Delaware River. This last estimate is an order-of-magnitude estimate made by analogy. Water supply was also estimated by analogy, using a Great Lakes water balance model. Walker et al. assumed that baseline demand would not increase above projected demand in 2030, potentially underestimating the increased demand for water and saltwater advance.

Walker et al. also estimated that a rise in temperatures consistent with the GISS and GFDL scenarios would mean about a 20% increase in cooling degree days.* In response, average daily demand for water used in cooling large buildings could increase by 190 million liters during the summer and increased lawn watering could raise demand by 110 million liters per day, thereby generating a 5% rise in annual demand.

Higher temperatures could increase evaporation and evapotranspiration, decreasing the ability to store water efficiently in surface impoundments. The water balance model indicated the supply loss could range from 10 to 24%.

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*The number of degrees by which the average daily temperature exceeds 65°F.

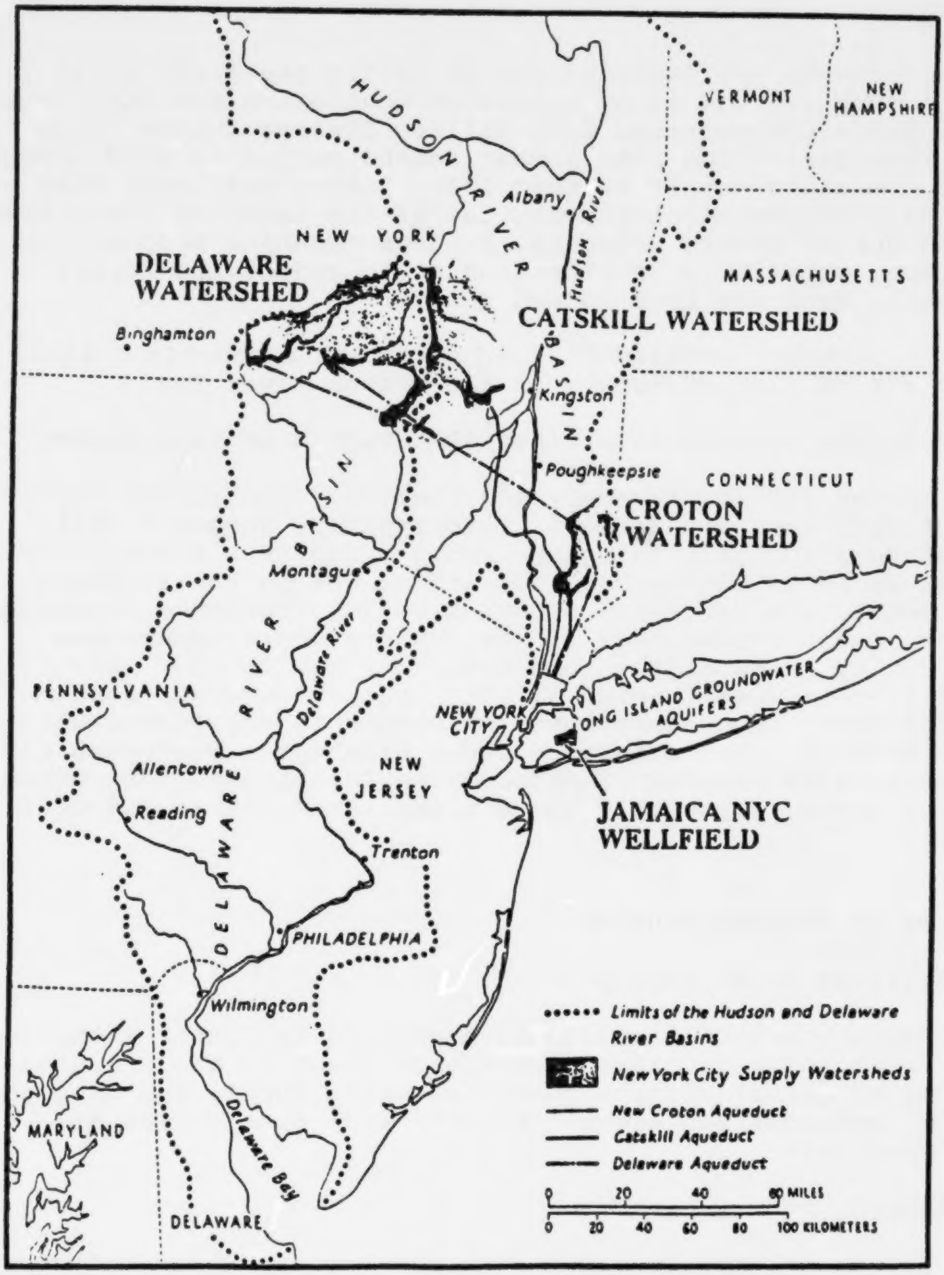
HUDSON RIVER BASIN
VERMONT
NEW HAMPSHIRE
Albany
Hudson River
NEW YORK
DELAWARE WATERSHED
MASSACHUSETTS
CATSKILL WATERSHED
Binghamton
Kingston
Poughkeepsie
CONNECTICUT
CROTON WATERSHED
Montague
DELAWARE RIVER BASIN
Delaware River
PENNSYLVANIA
LONG ISLAND GROUNDWATER AQUIFERS
NEW YORK CITY
NEW JERSEY
Allentown
Reading
JAMAICA NYC WELLFIELD
Trenton
PHILADELPHIA
Wilmington
Limits of the Hudson and Delaware River Basins
New York City Supply Watersheds
New Croton Aqueduct
Catskill Aqueduct
Delaware Aqueduct
MARYLAND
Delaware Bay
DELAWARE
0 20 40 60 MILES
0 20 40 60 80 100 KILOMETERS

Figure 15-1. The Sources of New York City's Water Supply.

Source: Citizen's Union Foundation of the City of New York, 1986.

Saltwater infiltration due to rising sea level would further reduce supply. The study suggested that a 1-m sea level rise could place the proposed $300 million Chelsea intake below the salt line during the peak summer demand period in mild drought years, reducing supply another 13%. Larger sea level rise or greater droughts might prevent use of the existing Poughkeepsie intake during severe droughts, further reducing supply. In addition, subsurface infiltration could reduce the supply available from the Long Island aquifer.

In summary, doubled CO_2 could produce a shortfall equal to 28 to 42% of planned supply in the Hudson River Basin.

Implications Arising From Other EPA Studies in This Report

Linder (1987), in analyzing national electricity demand (see Electricity Demand chapter of this report), suggests that increased air-conditioning use could raise peak electricity demand by 10 to 20% in New York and by 20% in the Southeast. Nationally, the northernmost areas would experience decreased demand, and the remainder of the country would experience electricity needs higher than currently estimated. Sheer's study of California (see Chapter 4) water supply suggests that new surface water impoundments may be needed to meet urban water and other demands. The coastal defense strategies suggested in the Sea Level Rise chapter (Chapter 9) would apply to most urban coastal areas, especially those along the Atlantic and Gulf coasts.

RESULTS OF RELATED STUDIES

Metropolitan Water Supply

Schwarz and Dillard (1988) conducted telephone interviews with local infrastructure managers to identify the probable impacts of global climate change on water supply and drainage in several metropolitan areas. Results from some cities are discussed here.

Washington, DC

Longer hot spells could warm the Potomac River and cause trihalomethane formed during chlorination to rise above allowable limits. Remedying this could require a capital investment of roughly $50-70 million and could increase treatment costs. Also, lawn watering probably would increase during long spells of hot, dry weather. Although a substantial decrease in runoff could reduce supply in parts of the system, the availability of additional storage capacity would make a shortage unlikely.

New Orleans

Sea level rise could necessitate moving the water intakes considerably farther up the Mississippi and replacing cast iron water mains that would corrode if exposed to salt water. Reduced river flow also could increase settling and treatment requirements. Rising sea level could increase saltwater infiltration into the water system and could require increased pumping capacity.

New York City

This study raised many of the same concerns regarding water supply and demand as the study by Walker et al. (Vol. X) and indicated that even a 0.25-m sea level rise would mean the proposed Chelsea intake was too far downstream. The sanitary and storm sewage system capacity and design probably would not need revision. Nevertheless, in a few low-lying areas, higher sea level could increase sewer backups, ponding, and basement flooding when high tides coincided with high runoffs.

Tucson

Tucson is depleting its aquifer despite substantial conservation efforts and lawn watering with treated wastewater. Higher temperatures would increase demand and tighten supply, possibly jeopardizing the city's ability to draw on water from the Central Arizona Project on the already strained Colorado River. While modest savings might be achieved through stricter conservation measures and more wastewater use, purchase of water in the regional market most likely would be the only practical response to climate-related shortfalls.

IMPLICATIONS FOR THE NATION'S URBAN INFRASTRUCTURE

The implications of climate change for urban America vary spatially. Some localities, especially those along the Great Lakes, might benefit. Others, especially those along the coastlines and in water-short areas, could face major infrastructure costs. The costs would be especially high if changes came through abrupt "sawtooth" shifts, making it difficult to adapt infrastructure primarily during normal repair and replacement. The likely impacts of an effective doubling of atmospheric CO_2 could affect a wide range of infrastructure.

Water

Hotter temperatures could cause faster evaporation of groundwater and raise the demand for water to support commercial air-conditioning systems and lawn watering. Larger winter rains in the West could force a lowering of dam levels to ensure availability of enough capacity to control flood waters. At the same time, sea level rise could cause saltwater to advance up rivers and to infiltrate into coastal aquifers. In droughts, many existing water intakes might deliver brackish water.

The solution to these problems could be expensive: strong conservation measures, miles of aqueducts from new water intakes at higher river elevations, new reservoirs, sewage effluent recycling systems to support commercial cooling or lawn watering, and perhaps desalinization efforts along the coasts. The solution for the New York-Philadelphia corridor alone is likely to cost $3-7 billion. Communities in the Delaware River Basin, northern New Jersey, the lower Hudson, and Long Island might well form a multi-State water supply and management district of unprecedented size and complexity to handle financing and capital construction.

Drainage and Wastewater Systems

Increased storm size and intensity could tax many storm sewer systems. Sea level rise also could reduce coastal flood protection levels in low-lying areas. The resulting increases in flooding and releases of untreated waste into watercourses from combined storm and wastewater systems probably would motivate new sewer investments. In Dade County alone, costs to maintain flood protection at existing levels could be $200-300 million if sea level rose 1 m.

Temperature rise could increase hydrogen sulfide formation in sewer pipes, leading to internal corrosion and eventual failure. In coastal areas, increased ocean flooding could increase how frequently storm sewers must carry corrosive saltwater. Sea level rise also could cause more pipes in coastal areas to face the external risk of corrosive seawater. More frequent inspection and earlier replacement of much existing pipe, as well as a gradual shift to more corrosion-resistant pipe with plastic lining, might be required.

Coastal Defenses

Protection from a rising sea could require tremendous investment in many major coastal communities. In urban areas, a common approach might be the New Orleans solution, where extensively developed coastal areas are protected by dikes, and covered drainage ditches behind the dikes are pumped to keep out the saltwater.

Roads

Rising temperatures could reduce the costs of road construction and maintenance. Snow and ice control costs might drop dramatically. A decrease in deep freezes and freeze-thaw cycles also would mean fewer potholes. Warmer temperatures and the improved drainage resulting from higher evaporation rates could permit use of thinner pavements in many areas, but require enhanced expansion capabilities.

Bridges

Sea level rise and increased storm intensity could require upgrading of many bridges either through costly retrofit or as part of normal reconstruction. The range of temperature accommodated by expansion joints also might need to be increased. The costs might be modest if bridge planners upgraded in anticipation of climate change.

Mass Transit

In the North, buses and railcars could experience fewer snow-related delays. Conversely, slight increases in fuel costs could result from increased use of air-conditioners.

Electricity and Air-Conditioning

Hotter temperatures could increase air-conditioning use. Consequently, peak load capacity to generate electric power might have to increase in response to global climate change. Fortunately, air-conditioning equipment is replaced fairly frequently, so increased loads on existing equipment could be accommodated incrementally. Some houses and public buildings in northern climates might need to add air-conditioning, but such retrofitting has been performed since the first window air-conditioners were introduced.

NATIONAL POLICY IMPLICATIONS

The uncertain, yet potentially imminent, impact of global climate change has already increased the risks of infrastructure investment. Application of design standards and extrapolation from historical data still may not provide reasonable assurance that water and power supply, dam strength and capacity, bridge clearances, or storm sewerage capacity will be adequate for the 35-, 50-, and 100-year design cycles of these facilities. For example, the National Flood Insurance Program's maps identifying the historical 100-year floodplain and 500-year floodway may no longer provide a reliable basis for local building and zoning ordinances designed to minimize flood losses to life and property.

Investment Analysis Methods

Especially in coastal areas, the possibility of accelerating global climate change may soon require careful decisions regarding how and when to adapt the infrastructure. A strong emphasis on life-cycle costing and upgrading during reconstruction in anticipation of future changes could yield large, long-term cost savings. To accomplish this goal such institutions as the Department of Housing might work with the American Public Works Association, the National League of Cities, the U.S. Conference of Mayors, the American Planning Association, and similar groups to educate their constituencies regarding the uncertainties and ways to incorporate them into the decisionmaking process.

Water Supply

Water supply is of particular concern because decades are required to plan and complete projects, which then might last 100 years. Dams, reservoirs, and water intakes currently being planned and built could become obsolete or inadequate as a result of global climate change. Elsewhere, communities might be allowing development of land needed for reservoirs to meet the water shortages that would result from climate change.

Such federal agencies as the U.S. Geological Survey, U.S. Army Corps of Engineers, and EPA may wish to work with States and municipalities to study the probable impacts of climate change scenarios on the water supply of major metropolitan areas.

Water supply investments frequently affect multi-State areas, creating a need for Federal coordination. The Supreme Court has been forced to settle previous water rights disputes concerning many major rivers, and global climate change might well generate new disputes. Cost-effective response to climate change also might require new multi-State water projects. For example, a major project on the Hudson River that allowed New York City to reduce its use of Delaware River water might be the least costly way to increase water supply in Philadelphia. The upcoming State debates over water supply financing should be informed by the lesson of past infrastructure crises: water piping and pumping costs resulting from global climate change should be fully recovered from the water users to avoid stimulating artificial demand for bargain water.

Infrastructure Standards

Voluntary standards organizations, such as the American Society of Civil Engineers, the Building Officials and Code Administrators International, and the American Association of State Highway and Transportation Officials, may wish to educate their committees on global climate change. Growing uncertainty concerning future temperature, precipitation, and sea levels might dictate a reassessment of existing standards and safety factors for ventilation, drainage, flood protection, facility siting, thermal tolerances, resistance to corrosion, and so forth. Conversely, prompt detection of lasting changes could allow adjustment of geographically based standards -- for example, on roadbed depth and home insulation levels -- and provide significant savings. Thus, the standard-making organizations might beneficially establish policies concerning how and when their committees should account for global climate change or educate their committees about the prospects.

Voluntary standard organizations, such as the American Society of Civil Engineers, the Building Officials and Code Administrators, International and American Society of Heating and Refrigerating and Air Conditioning Engineers should examine the need for changes in existing standards to improve the use of energy and safety factors.

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DRAFT

CHAPTER 16

NATIONAL IMPACTS OF CLIMATE CHANGE ON ELECTRIC UTILITIES

FINDINGS

Global warming would increase electricity demand, generating capacity requirements, annual generation, and fuel costs. The impacts could be significant within a few decades, and would increase substantially over time if global warming continues.

- By 2010, new generating capacity requirements induced by climate change are estimated to increase by 25 to 55 gigawatts (GW) or 9 to 19 percent above estimated new capacity requirements, assuming no change in climate. Between 2010 and 2055, climate change impacts could accelerate, increasing new capacity additions by 200 to 400 GW (14 to 23 percent) above what would be needed in the absence of climate change. These capacity increases would require investments of approximately $200 to $300 billion. These results are sensitive to assumptions about the rates of economic growth, technological improvements, and the relationship between energy use and climate. The savings in other fuels (gas and oil) in northern regions and the impacts on hydroelectric supplies were not analyzed.

- Estimated increases in annual electricity generation and fuel use induced by climate change represent several thousand gigawatt-hours by 2055. The estimated increases are 1 to 2 percent in 2010 and 4 to 6 percent in 2055. Annual fuel, operation, and maintenance cost would be hundreds of millions of dollars in 2010 and several billion dollars in 2055.

- Estimated regional impacts differ substantially for the scenarios studied. The largest increases would occur in the Southeast and Southwest, where air conditioning costs are large relative to heating. Northern border states may have a net reduction in electricity generation relative to base over increases in generation capacity.

Policy Implications

- Utility executives and planners should begin to consider climate change as a factor in planning new capacity. The estimated impacts of climate change is similar to other uncertainties and issues utility planners may need to consider over the 20-30 year period. Additional climate and utility analyses are needed to develop refined risk assessments and risk management strategies.

- The increased demand for electricity induced by climate change also could offset other environmental problems, such as the implementation of "acid rain" strategies, adherence to the international NO_x treaty, state implementation plans for ozone control, and thermal pollution control permit requirements. The Environmental Protection Agency should analyze the impacts of climate change on long-range policies and should include climate change as an explicit criterion in making risk management decisions when appropriate.

- The increased demand for electricity could make policies to stabilize the atmosphere through energy conservation more difficult to achieve. The estimated increases in electricity generation induced by climate change alone could increase annual CO_2 emissions by 40-65 million tons in 2010 and by 250-500 million tons in 2055. This does not consider reduced demand for oil and gas in residential furnaces for heating. Future analyses of national and international strategies to limit greenhouse gases should include the additional energy demand created by global warming as a positive feedback.

CLIMATE CHANGE AND ELECTRICITY DEMAND

While climate change could affect a wide range of energy sources and uses, its implications with regard to the demand and production of electricity could be significant. Many electrical end uses vary with weather conditions. The principal weather-sensitive end uses are space heating and cooling and, to a lesser degree, water heating, cooking, and refrigeration. These applications of electricity may account for up to a third of total sales for some utilities and may contribute an even larger portion of seasonal and daily peak demands. (Electric energy used for air-conditioning exceeds that used for space heating nationwide, and the temperature-sensitivity associated with cooling is higher than that associated with heating.)

Changes in weather-sensitive demands for electricity can affect both the amount and the characteristics of generating capacity that a utility must build and maintain to ensure reliable customer service. These changes also can affect fuel requirements and the characteristics of efficient utility system operations, particularly the scheduling and dispatching of the utility's generating capacity.

Similarly, utilities in most regions experience their peak demands in the summer. A rise in air-conditioning and other temperature-sensitive summer loads could significantly increase peak loads and, as a result, would step up utility investments in new generating capacity needed to meet additional demands and to maintain system reliability.

PREVIOUS CLIMATE CHANGE STUDIES

A number of utilities conduct analyses relating short-term variations in weather conditions with a need to "weather-normalize" historical demand data and to test the sensitivity of system reliability and operations to these short-term variations. Furthermore, some researchers have speculated regarding the potential effects of longer term climate changes on electricity demand (e.g., Stokoe et al., 1987).

However, only one previous study has estimated the potential implications of longer term, global warming-associated temperature changes on electricity demands and on utility investment and operating plans. Linder et al. (1987) used General Circulation Model (GCM) results to estimate the potential impacts of temperature change on electricity demand and on the supply of hydropower for selected case study utility systems in two geographical areas: a utility located in the southeastern United States and the major utilities in New York State, disaggregated into upstate and downstate systems.

Linder et al. found that temperature increase could significantly heighten annual and peak electricity demands by 2015, and that a temperature rise would require construction of new generating capacity and increases in annual generation. The southeastern utility had higher estimated increases in electricity demand, generation, and production costs than the New York utilities because of greater electricity demands for air-conditioning. In addition, streamflow used to generate hydropower in New York could be reduced, requiring increased use of fossil fuel generation to meet customer demands for electricity.

CLIMATE CHANGE STUDY IN THIS REPORT

Study Design

Linder and Inglis[1] expanded on the regional case studies of the sensitivity of electricity demand to climate change by conducting a national analysis of electricity demand. The national analysis used the same basic approach as that used in the regional case studies. Relevant regional results from Linder's national studies are discussed in the regional chapters of this report.

The analytic approach developed by Linder et al. formed the basis for estimating the regional and national impacts described in this report. The principal steps in the approach are summarized in Figure 16-1 (see Volume X for more details). Estimated impacts were developed for the relatively near term (from the present to 2010, within electric utility long-range resource planning horizons of 20-30 years) and over the longer term (to 2055), when the magnitude of temperature changes is expected to approach equilibrium levels representative of a doubling of atmospheric concentrations of CO_2. Linder and Inglis used Goddard Institute for Space Studies (GISS) A and B transient estimates of temperature change in 2010 and 2055 in his calculations. The changes in annual temperatures for the utility regions ranged from about 0.6 to 1.6°C in 2010 and from about 3.1 to 5.3°C by 2055.

Linder and Inglis used actual utility demand and temperature data from the case study utilities, and from five other large, geographically dispersed utility systems to develop a set of weather-sensitivity parameters for utility areas. On a weighted-average basis (weighted by electricity sales), utility peak demands were estimated to increase by about 3.1% per change in degree Celsius (ranging from -1.35 to 5.40% across utility areas), and annual energy demands were estimated to increase by about 1.0% per change in degree Celsius (ranging from -0.54 to 2.70%).

A number of uncertainties associated with the data and assumptions used to develop these weather-sensitivity relationships suggested that the relationships may understate customer response to climate change, particularly at higher ,

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[1] The Potential Impact of Climate Change on Electric Utilities: Regional and National Estimates -- Linder and Inglis, ICF, Inc.

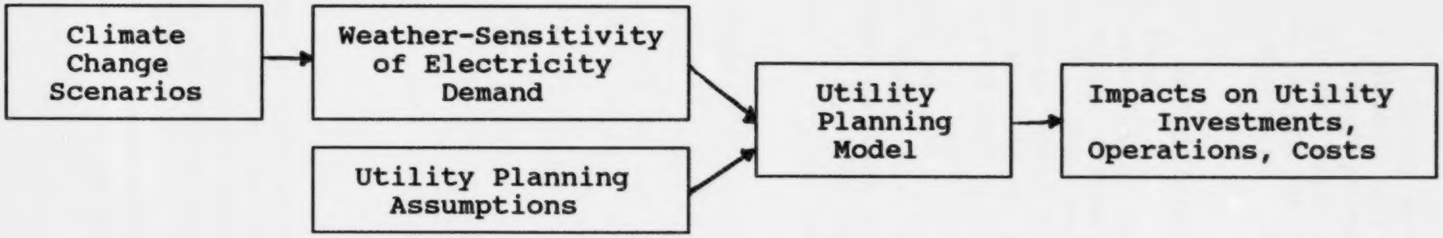
Climate Change Scenarios
Weather-Sensitivity of Electricity Demand
Utility Planning Assumptions
Utility Planning Model
Impacts on Utility Investments, Operations, Costs

Figure 16-1. Analytic Approach

Source: Linder and Inglis, Volume __.

temperature change levels occurring in the future. For example the approach did not explicitly account for probable increases in the market saturation of air-conditioning equipment as temperatures rise over time. To address this possibility, an alternate case was designed in which the estimated weather-sensitivity values were increased by 50%. This was designated as the "higher sensitivity" case.

Since this study is focused on estimating how climate change may affect key utility planning factors, Linder used a planning scenario assuming no change in climate (a "base case") to serveas a basis for comparison with planning scenarios under alternative assumptions of climate change for 2010 and 2055. Thus, base case utility plans were developed for 2010 and 2055, using assumptions regarding future demands for electricity in the absence of climate change, generating technology option performance and costs, fuel costs, and other utility characteristics. Linder and Inglis assumed that future capacity and generation requirements will be met by investments either in new coal-fired baseload capacity or in oil- and natural gas-fired peaking capacity. Other sources, such as nuclear energy and renewables or innovative fossil fuel-fired technologies (e.g., fluidized bed combustion) were not considered.*

Demands for electricity in the absence of climate change can be related to the overall level of economic activity as represented by the gross national product (GNP). Because of the critical nature of economic growth, alternative GNP growth rates were assumed in developing the base cases; these ranged from 1.2 to 2.1% per year.** These alternative assumptions are referred to as "lower growth" and "higher growth," respectively.

These assumptions served as inputs to a regional planning model called the Coal and Electric Utilities Model (CEUM). CEUM output includes the amount and characteristics of new generating capacity additions, electricity generation by fuel type, and electricity production costs.

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*Innovative technologies will penetrate future power markets. However, the analysis for this focused on distinction between requirements for peaking capacity vs. baseload capacity generally and not on utility investments in specific types of technologies.

**These GNP growth rates are relatively conservative, but they are comparable with GNP growth rates used by EPA in its Report to Congress on atmospheric stabilization.

Limitations

The study did not include analysis of temperature sensitivity for all utility regions of the United States. It focused narrowly on impact pathways, considering only the potential effects of temperature change on changes in electricity demand. Neither the potentially significant impacts of climate change on hydropower availability nor the impacts of reduced water supplies for cooling were included.

Furthermore, the study did not evaluate the sensitivity of the results to different GCM climate scenarios, although the use of the GISS transient experiment results for 2010 and 2055 indicates relative sensitivities to small and large temperature changes.

Very limited climate change information important for utility planning was available (e.g., variations in temperature changes and the occurrence of extreme events, which affect powerplant dispatch and determinations of peak demands, respectively).

Many uncertainties exist regarding the concepts, methods, and assumptions involved in developing and applying estimates of the temperature sensitivity of demand. For example, a key assumption is that the estimated sensitivities of demand to historical, short-term variations in temperature are adequate representations of future relationships between electricity demand and long-term changes in mean temperatures.

Uncertainties also exist regarding market, regulatory, technological, and other conditions that will face the utility industry in the future. For example, technological changes that improve the energy efficiency of weather-sensitive end-use equipment or electricity-generating equipment could reduce the estimated impacts of climate change.

Results

The potential national impacts for 2010 and 2055 are summarized in Table 16-1. The table presents base case values (i.e., assuming no change in climate) for each year and estimated impacts represented by changes from the base case values. The impacts for 2055 are presented for both the lower growth GNP and the higher growth GNP cases. Also, where ranges of impacts are presented, they summarize the estimates under alternative climate change scenarios (GISS A and GISS B) and assumptions of the

TABLE 16-1. The Potential National Impacts of Climate Change on Electric Utilities

	2010		2055			
			Lower GNP		Higher GNP	
	Base	**Increase**	**Base**	**Increase**	**Base**	**Increase**
Peak demand (GW)	774	20-44	1,355	181	1,780	238-357
New capacity reqirements (GW)[a]						
Peaking	50	13-33	176	118	254	182-286
Baseload	226	11-22	1,011	67	1,423	74- 98
Total	376	24-55	1,187	185	1,677	227-384
Annual sales (bkWh)	3,847	39-67	6,732	281	8,848	370-555
Annual generation[b] (bkWh)						
Oil/gas	287	(12)-(29)	221	2	308	27- 51
Coal	2,798	54-103	6,242	305	8,295	381-560
Other	1,092	1- (1)	846	(2)	1,003	(7)- 0
Total	4,177	43- 72	7,309	305	9,607	401-611
Cumulative capital costs[c] (billions of 1986 $)	669	25-48	1,765	173	2,650	222-328
Annual costs (billions of 1986 $)	162	3-6	474	33	655	48-73

[a] Includes reserve margin requirements; does not include "firm scheduled" capacity.
[b] Includes transmission and distribution losses.
[c] "Base" values include regional capital expenditures for utility-related equipment in addition to new generating capacity (e.g., new transmission facilities).

Abbreviations: GW = gigawatts; bkWh = billion kilowatthours.
Source: Linder and Inglis, Volume __.

weather sensitivity of demand ("estimated sensitivity" and "higher sensitivity").

Estimated increases in peak demand on a national basis range from 2 to 6% by 2010. Changes in estimated annual energy requirements by 2010 are more modest, ranging from 1 to 2%. In 2055, peak national demands are estimated to increase by 13 to 20% above base case values, and annual energy requirements are estimated to increase by 4 to 6%. By 2010, new climate change-induced generating capacity requirements increase by 6 to 19%, or about 24 to 55 GW, representing an average increase of up to 1 GW per State (approximately the capacity of a large nuclear or coal-fired baseload powerplant). The majority of the capacity increase is for peaking capacity rather than baseload capacity. The investment associated with these capacity increases is several billion dollars (in constant 1986 dollars). By 2055, the change in new capacity requirements increases in percentage terms and represents several hundred GW. Under high GNP and higher weather-sensitivity assumptions, the estimated increase attributable to climate change is almost 400 GW, or 23%.

Annual generation increases for the United States are not as large in percentage terms as those estimated for new generating capacity requirements, but nonetheless, they account for several hundred billion kWh by 2055. In the near term (i.e., to 2010), increased levels and changing patterns of climate change-induced electricity demand permit utilities in some areas having excess generating capacity to serve the growing needs of utilities in other areas through substitution of lower cost coal-fired generation for higher cost oil- and natural gas-fired generation. On net, oil- and gas-fired generation would be lower owing to climate change in 2010.* In 2055, oil- and gas-fired generation is projected to increase along with coal-fired generation, because all the excess capacity that had existed in 2010 either would have been fully used by growing demands to 2055 or would have been retired. The estimated impacts of climate change on national new generating capacity requirements and annual generation are illustrated in Figure 16-2.

Table 16-1 also indicates that the increase in annual costs for capital, fuel, and O&M associated with climate change-induced modifications in utility investments and operations are a few

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*This result is confirmed and explained in more detail in the case study report (Linder et al., 1987).

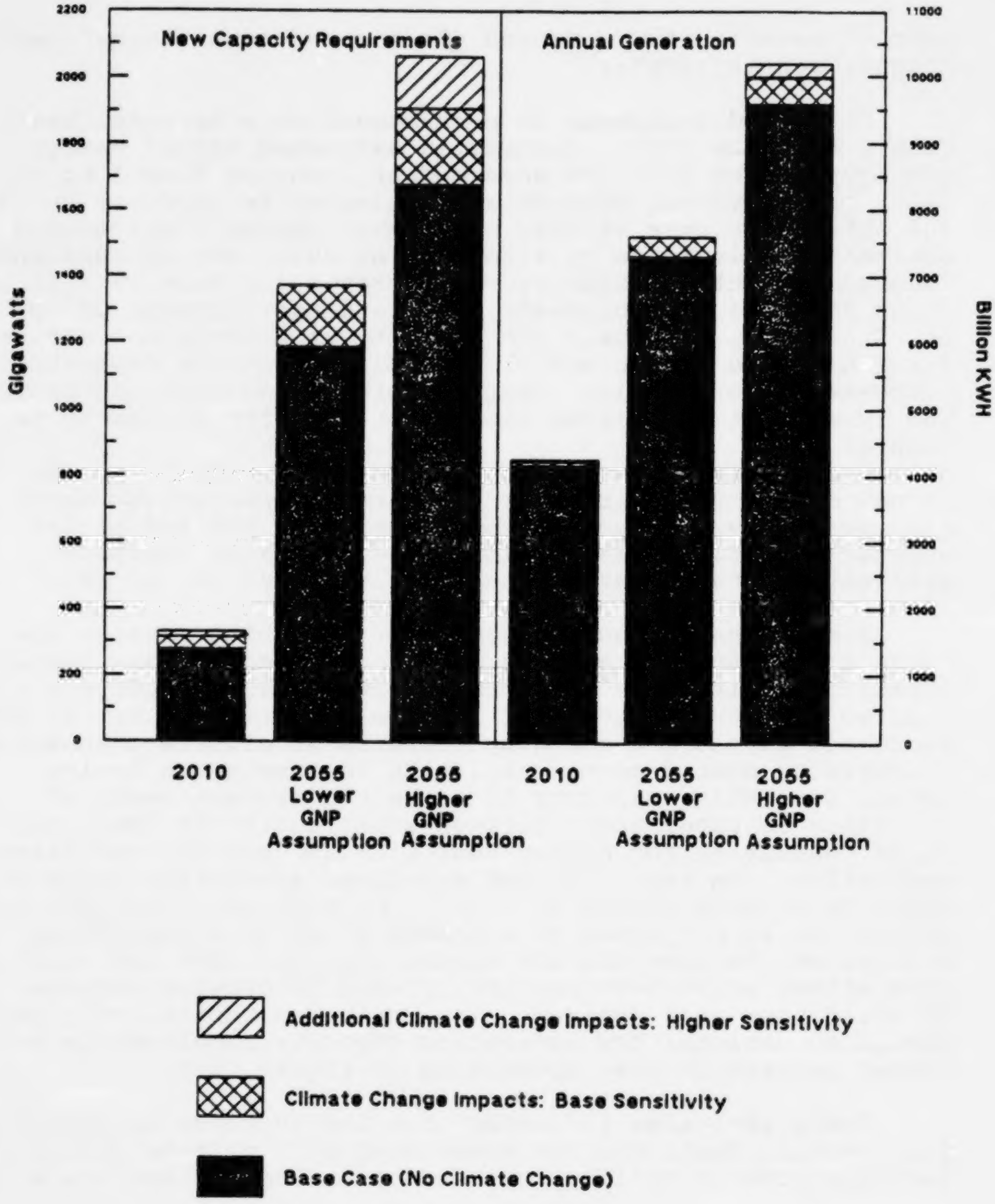

Figure 16-2. Potential impacts of climate change on electric utilities, United States

Source: Linder and Inglis, Volume __.

billion dollars in 2010 and are $33-73 billion by 2055, a 7 to 15% increase over base case values for 2055.

Figures 16-3 and 16-4 illustrate the diversity of the estimated results for generating capacity on a state-by-state basis. The State and regional differences reflect differences in current climate conditions (e.g., seasonal temperature patterns), assumed future climate changes, and electricity end-use and utility system characteristics (e.g., market saturation of weather-sensitive appliances and equipment).

Figure 16-3 shows that estimated reductions in new capacity requirements induced by climate change are limited to the winter-peaking regions of the extreme Northeastern and Northwestern States. The Great Lakes, Northern Great Plains, and Mountain States, as well as California, are estimated to experience increased new capacity requirements by 2055 in the range of 0 to 10%. Increases greater than 20% are concentrated in the Southeast, Southern Great Plains, and Southwest.

Figure 16-4 shows a somewhat similar geographic pattern of impacts for electricity generation in 2055. Reductions in generation are estimated in the Northern States, and the greatest increases are concentrated in the Southwest. Despite substantial use of air-conditioning in the Southeast, the estimated increases in generation are only in the 5 to 10% range. There is a relatively high market saturation of electric heat in the region, and the increase in cooling is partly offset by a decrease in heating as a result of warmer winters.

Because regions are affected differently, the results indicate potential changes in the patterns of interregional bulk power exchanges and capacity sales overtime and as climate change. For example, under the assumption of increasing temperatures, some regions may require significant amounts of additional generating capacity to meet increased demands reliably during peak (cooling) seasons, but may experience lower demands in other (heating) seasons. As a result, the region's needs may be for power plants that are utilized heavily during only part of the year. Low annual utilization in the region would not justify construction of high capital and low fuel cost baseload power plants that can produce electricity more cheaply (per kwh) than low capital and high fuel cost peaking units. However, when considered across several regions, the least-cost plan may be to construct baseload power plants in certain regions, utilize them to an extent greater than required by the region, and sell the "excess" electricity from these plants into other regions. The

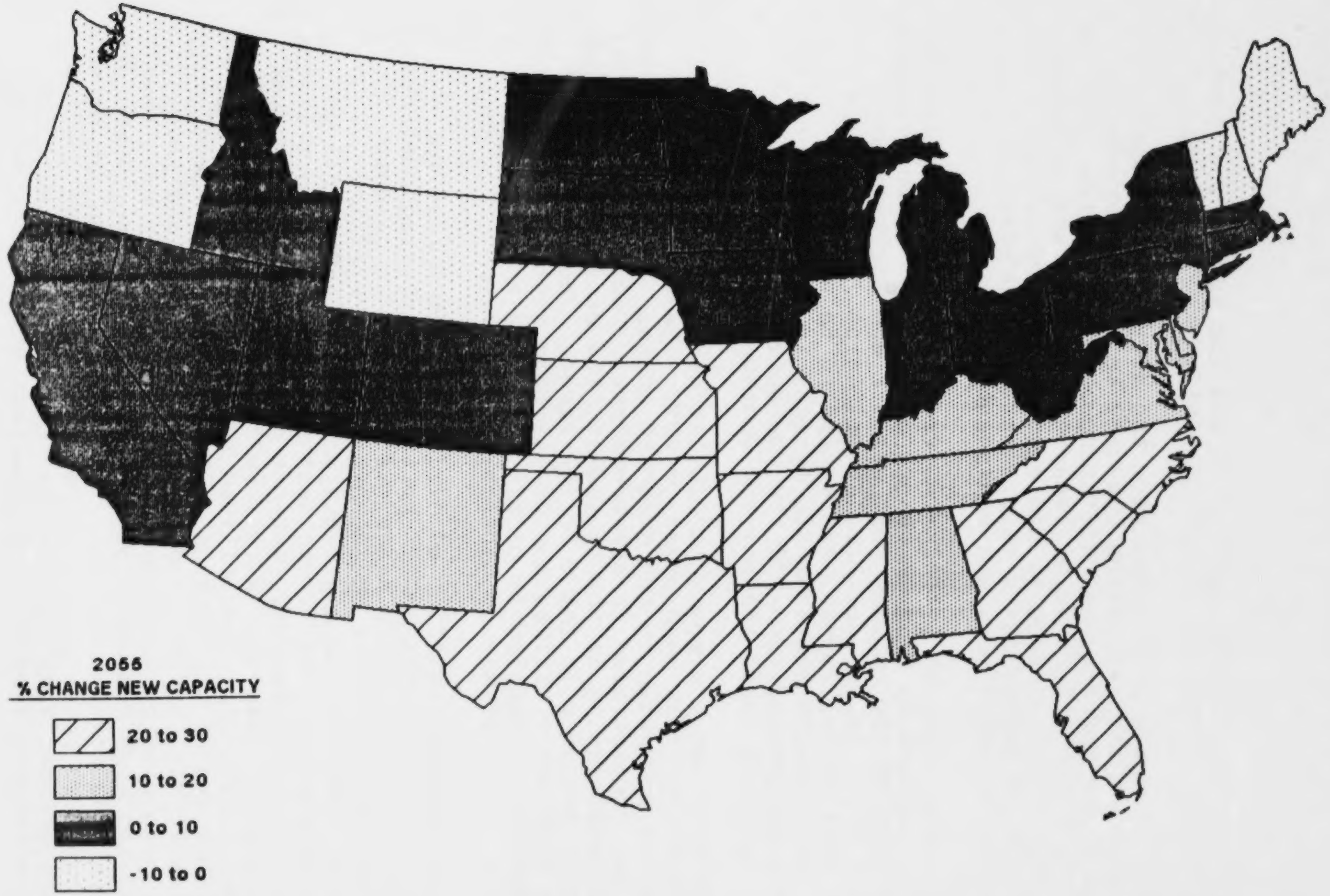
2055
% CHANGE NEW CAPACITY
▨ 20 to 30
10 to 20
■ 0 to 10
-10 to 0

Figure 16-3. Changes in electric utility capacity additions by state: induced by climate change to 2055.

Source: Derived from Linder and Inglis, Volume __.

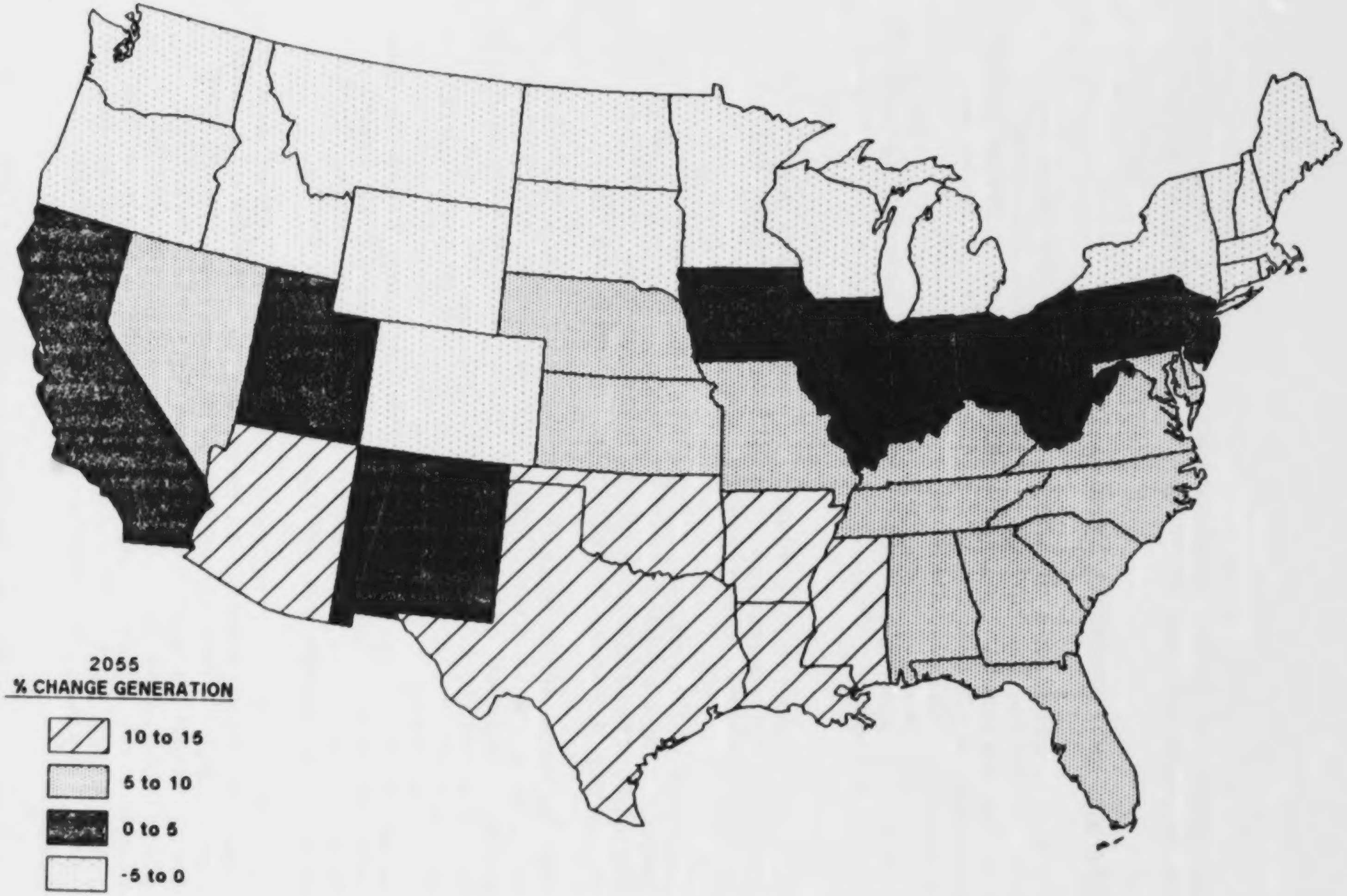
2055
% CHANGE GENERATION
10 to 15
5 to 10
0 to 5
-5 to 0

Figure 16-4. Changes in electricity generation by state: induced by climate change in 2055.

Source: Derived from Linder and Inglis, Volume __.

location and amount of these interregional sales would be subject to the transfer capabilities of transmission capacity in place.

SOCIOECONOMIC AND ENVIRONMENTAL IMPLICATIONS

Despite the limitations of the analysis and the need for more research to refine the data and methods used, the results are judged to be reasonable estimates of potential climate change impacts associated with temperature change and its effects on electricity demand. Key socioeconomic and environmental implications of the results stem from the increases in electric generating capacity and generation requirements associated with climate-induced changes in demand. The implications include the following:

- Climate change could result in overall fuel mixes for electricity generation that differ from those expected in the absence of climate change.
- Regional differences in capacity and generation requirements suggest that important, new opportunities for interregional bulk power exchanges or capacity sales may arise as a result of climate change.
- The impacts of uncertain climate conditions over the long term could pose significant planning and economic risks. Because of long lead times required to plan and build economic baseload generating capacity, the ability of utility planners to correctly anticipate climate change could result in lower electricity production costs. The magnitude of these risks in some regions (e.g., the Southeast and the Southern Great Plains) could be similar to other uncertainties that utility planners and decisionmakers must face.
- If the result is confirmed that the majority of new capacity requirements in response to climate change are for peaking capacity, a new technological and market focus would be directed at this type of generating plant. Related to this would be increased R&D on electricity storage technologies, which would allow lower cost, more efficient powerplants to generate, at off-peak times, electricity for use during peak periods.
- Because increases in customer demands for electricity may be particularly concentrated in certain seasons and

at peak periods, conservation and especially load management programs that improve the efficiency or change the patterns of customer uses of electricity could be more cost-effective when considered in the context of potential changes in climate.

- Increased demands could increase electricity imports, adversely affecting the U.S. balance of payments.

- Increased electricity generation implies increased adverse environmental impacts associated with the following:

  - air quality (e.g., emissions of sulfur dioxide, NO_x, and other pollutants);
  - land use for new powerplant sites, fuel extraction, fuel storage, and solid waste disposal;
  - water quality and use (e.g., for powerplant cooling and fuel processing); and
  - resource depletion, especially of such nonrenewable fuels as natural gas, which may be in short supply.

  Of particular concern would be additional water withdrawal and consumption requirements in areas where water supplies may be reduced by climate change.*

- Increased electricity generation also implies increased emissions of CO_2 and other greenhouse gases. For example, if the estimated increases in climate change-induced generation reported in Table 16-1 were met by conventional technologies, CO_2 emissions could increase by 40-65 million tons per year by 2010 and by 250-500 million tons per year by 2055.[**]

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*For example, increased electricity generation induced by climate change in Northern California could increase requirements for water withdrawal by 600-1,200 million ft^3 and for water consumption by 200-400 million ft^3 in 2055. Comparable figures for the Southern Great Plains in 2055 would be water withdrawal of 5,800-11,500 million ft^3 and consumption of 1,800-3,500 million ft^3.

POLICY IMPLICATIONS

In general, the study results suggest that utility planners and policymakers should begin now to assess more fully and to consider climate change as a factor affecting their planning analyses and decisions. If more complete and more detailed analyses support the socioeconomic and environmental implications of the climate change effects described above, they should be explicitly addressed in planning analyses and decisions.

Specific policy implications related to the findings include the following:

- In formulating future National Energy Plans, the Department of Energy may wish to consider the potential impacts of climate change on utility demands.
- The interactions of climate change and the current efforts of the Federal Energy Regulatory Commission (FERC) to restructure the electric utility industry are difficult to assess. For example, the industry's response to FERC policies could either accelerate or reduce the rate of emissions of greenhouse gases, depending upon changes in the mix of generating fuels and effects on the efficiency of electricity production. The possible, alternative responses should be assessed, and FERC policies should be considered with respect to their potential implications related to climate change issues.
- Increases in electricity demands induced by climate change will make achievement of energy conservation goals more difficult. For example, the draft conference statement from "The Changing Atmosphere: Implications for Global Strategy" (Environment Canada, 1988) calls for reductions in CO_2 emissions to be achieved in part through increased efforts in energy efficiency and other conservation measures. An initial

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[**] Note, however, that these increases in emissions from electricity production could be offset at least in part by reduced demand for space heating provided by natural gas and oil furnaces or by other direct uses of fossil fuels.

goal for wealthy, industrialized nations set by the conference is a reduction in CO_2 emissions through conservation of approximately 10% of 1988 emissions levels by 2005. The impacts of climate change to increase electricity demand should be factored into the policies and plans designed to achieve this conservation goal.

- Similarly, climate change impacts may exacerbate the difficulties or costs associated with implementing acid rain mitigation strategies being considered by the Congress. However, these strategies center primarily on near-term solutions focusing on emissions reductions from existing powerplants, and the impacts of climate change may not be large within that time frame.

RESEARCH NEEDS

Important areas for further climate change research include improved methods for developing and disseminating climate change scenarios, with particular emphasis on (1) estimates of variables (in addition to temperature) relevant to impact assessment (e.g., hydrologic factors, winds); (2) estimates of the possible impacts of global warming on variations in weather conditions and the occurrence of extreme events; (3) continued attention to estimates of the rate of climate change over time; and (4) estimates of climate change at a more disaggregated regional or local level.

Follow-on research suggestions on the utility side include (1) refinement of the analytical approach, in part through lessons learned from additional utility-specific analyses; (2) more detailed and complete analyses of the weather sensitivity of customer demand for electricity; (3) extension of the approach to consider other pathways (including indirect and secondary effects) in which climate change could affect utility investments and operations; and (4) an assessment of the value of improved climate change information to utility planners and managers.

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CHAPTER 17

ANALYSIS OF CLIMATE VARIABILITY AND EXTREME EVENTS

FINDINGS

Climate variability is an important factor needed for detailed climate impact studies. Analysis of changes in variability estimated by two GCMs is inconclusive. Inconsistencies are obtained in comparing the changes in climatic variability with a changing climate calculated by two different global circulation models (GCMs) in four regions of the United States.

  - For interannual variability the GISS model produces reduced variability for temperatures for January - April but varied results for the other months. The interannual variability of precipitation tends to increase, although not consistently.

  - The GISS model suggests reduction in the variability of daily temperature with warming, but these results are not statistically significant on a regional-by-regional basis. The NCAR model (Washington version) produces both increases and decreases in daily temperature variability (although most of these changes are not statistically significant). The daily variability of precipitation with a warming climate tends to increase in the majority of cases (months and locations).

  - The amplitude of the diurnal cycle (GISS results) tends to decrease in summer with warming. In the other seasons, both increases and decreases occur.

- On the basis of the mixed model results on how climatic variability will change with a changed climate, the assumption of no change in variability in the scenarios used for this report must be recognized as reasonable, given the current state of knowledge.

- Comparison of observed and model results for the current climate for the two GCMs for selected regions of the United States reveals both interesting contrasts and similarities regarding the reproduction of climate variability.

  - Regarding mean statistics for temperature and precipitation, there are significant discrepancies in both models, compared to observed values in all four regions examined. The GISS model is in general too cool in summer and fall, whereas the NCAR model is either too warm or too cool, depending on the region and the time of year. Errors for both models are in general on the order of several degrees C. The GISS model and the NCAR model (Chervin version) consistently overpredict precipitation in the four regions.

- Additional comparisons of mean values of precipitation and temperature with two additional versions of the NCAR model revealed both under and over estimations of mean precipitation, whereas mean annual temperature was consistently overestimated.
- The interannual variability of relative humidity and absorbed radiation (NCAR results) are fairly well reproduced by the model, but tend to be slightly lower than the observed. The daily variance of relative humidity is much lower than the observed at all locations examined.
- The GISS model overestimated interannual variability of temperature, whereas the NCAR model (Chervin version) tends to underestimate it. Both models reproduce the variability "reasonably well" at some locations some of the time.
- Both models reproduce the relative variability of annual precipitation fairly well at all locations, although the GISS model overpredicts the absolute variability. There are indications that both models fail to properly reproduce the daily variability of precipitation. Both underestimate the frequency of light rain days, and overestimate the frequency of high-intensity rain days.
- Explanations for some discrepancies, such as why the daily variances of temperature are too high, relate to how the surface hydrology is modeled in both models. More investigations of model results are necessary in order to improve understanding of future changes in climate variability.

NATURE AND IMPORTANCE OF CLIMATE EXTREMES

The impacts of climate change on society accrue not necessarily from the relatively slow trends in the mean of a climate variable, but rather from the attending shifts in the frequency of extreme events. This issue has already received some attention in the literature (e.g., Schwarz, 1977; Parry, 1978; Mearns et al., 1984) where the nonlinear relationship between changes in the mean and extreme events has been underlined. However, less is known about this factor than about most other aspects of climate change.

For the purposes of climatic impact analysis, Heathcote (1985) states that extreme climatic events may be considered "short term perturbations of the energy flows which provide magnitudes outside the normal spectrum or range of the typical period." What constitutes normal is, of course, a central issue in defining extremes as well as what constitutes the averaging period.

Extreme events relevant to impact analysis function in different time scales, depending upon the climate variable involved and the impact area of interest. Thus, events can range from the length of time (in minutes and hours) that minimum temperatures in Florida remain below a critical value, resulting in damage to citrus crops, to the length of time (in months and years) that precipitation is particularly low in California, resulting in serious water shortages for industry and agriculture. The probability of extreme events can also vary considerably, for example, a range from recurrence intervals for extreme snowfall in the Buffalo, New York, area of a magnitude similar to that of the 1976-77 winter (1/20,000 or 0.00005), to heat waves (temperatures above 100°F for 5 consecutive days) in Dallas, Texas (0.38).

What defines an event as extreme is not only a certain statistical property (for example, likely to occur less than 25% of the time), but also how prepared a particular system is to cope with an event of such magnitude. Hence very few extreme events have a fixed absolute value independent of particular response systems at a particular location. This implies that what constitutes an extreme event can also change over time due to changes in the relevant response system (Heathcote, 1985).

It is thus very difficult to comprehensively review all climatic extreme events of importance to society, and what is presented here is far from an exhaustive catalogue. Because one of the purposes of this review is to highlight the extreme events of importance that can serve as guides for choosing the extreme events that should be quantitatively analyzed in general circulation model (GCM) doubled CO_2 experiments, priority is given to events related to relatively easily analyzable variables.

This review considered the two most important climate variables and their extremes (maxima and minima) and one major meteorological disturbance: temperature, precipitation, and severe storm effects. Extremes in these variables affect the areas of energy use and production, human mortality and morbidity, agriculture, and unmanaged ecosystems (although not all areas are discussed under each climatic extreme event). It should be noted that although the research on extreme climate events not as extensive for natural ecosystems as for some of the other are as covered here, in present research on climatic change impacts on forest ecosystems, the primary importance of variability changes has been underlined (e.g., by Soloman and West, 1985) who assert that climate variance controls geographic ranges of mature tree species, and the rates and outcomes of plant succession; and in chapter 11 of this report where limitations of the EPA forest studies since they did not consider change in climate variability, are discussed).

Temperature

Given the scientific consensus that higher atmospheric concentration of greenhouse gases will raise average global temperatures, extreme temperature effects are given priority in this analysis.

Maximum Temperatures

The area of extreme temperature effects that has received the most attention in the scientific literature is the effects on human mortality and morbitidity (e.g., Kalkstein, 1988; Becker and Wood, 1986; Jones et al., 1982; Bridger et al., 1976; and Ellis, 1972). This is partly because the relevant climatic factors (i.e., maximum daily temperatures and relative humidity) are readily available for analysis.

Heat waves consist of a series of days with abnormally high temperatures. Examples include the 1980 heat wave in the United States when Kansas City had 17 consecutive days above 102°F, St. Louis had 16 days above 100°F (Jones et al., 1982), and Dallas had 42 consecutive days with temperatures above 100°F (Becker and Wood, 1986). The death toll that year was several times above normal (1,265 lives). Major heat waves of at least regional extent in the United States in this century occurred in 1901 (9,058 deaths in the Midwest), 1934, 1935, and 1936 (4,768 deaths nationwide in 1936 alone), 1954, 1955, 1966, and 1980.

Studies have specifically tried to pinpoint the most significant meteorological factors associated with heat-related death and illness. Oeschli and Buechley (1970) identified the maximum temperature with a 1-day time lag for three Los Angeles heat waves. Jones et al. (1982) determined that high maximum temperatures, the number of days that the temperature is elevated, high humidity, and low wind velocity contributed to excess mortality in Kansas City and St. Louis in the 1980 heat wave. Kalkstein et al. (1987) established for New York City that runs of days with high minimum temperatures, low relative humidities, and maximum temperatures above 92°F contributed to heat-related deaths. In a more comprehensive study (reviewed in Chapter 14, Health), Kalkstein (1988) established statistical models relating weather and mortality to heat intensity.

Increases in heat waves are virtually certain, assuming global warming. But how they increase (longer or greater departure from the mean) very much depends on changes in variability that would affect the persistence of high temperatures.

Such crops as corn, soybeans, wheat, and sorghum are sensitive to high temperatures during their bloom phases. For example, Shaw (1983) reported that severe temperature stress during a 10-day period around silking will result in crop failure. Corn silking is a very critical period, during which the number of kernels on the ear are determined. Barnell and Eftmescu (1973) reported that maximum temperatures exceeding 32°C around tasseling and silking resulted in high rates of kernel abortion. Thompson (1968) developed a statistical model to determine corn yields and found that the accumulation of daily maximum temperatures greater than 92°F in July and August was negatively correlated with yield. McQuigg (1981) reported that the corn crop was severely damaged in July 1980 as a result of temperatures exceeding 100°F. The destructive effects of runs of hot days on corn yields was particularly in evidence in 1983 in the U.S. Corn Belt. Although the damage from high temperatures is best documented for corn, it has also been noted in wheat and soybean yields (e.g., Neild, 1982; Mederski, 1983).

Although not as much research has been performed on the effects of temperature extremes on natural ecosystems, some research has been done on forest responses to temperature extremes. Solomon and West (1985) indicate in their summary of climate effects on forests that the frequency, intensity, and lengths of heat waves under climate change conditions are important factors influencing seedling survival, and can contribute to the loss of a species from an ecosystem. A run of warm years can affect the location of tree lines. Schugart et al. (1986) established that a period of warm summers at high altitudes during the 1930s, when the mean annual temperature was no more than 1°C higher than average, resulted in a burst of regeneration in boreal forest trees near polar and altitudinal limits in North America.

High temperatures have their most immediate impact on energy by causing an increase in demand for electricity for air-conditioning. In a report prepared for New York State, the potential impacts of climate change on electric utilities were investigated. Using climate scenarios similar to those used by EPA (see Chapter 3), Linder et al. (1987) found that energy demand would significantly increase in summer (on the order of 3% for an average August day in 2015 for downstate New York). Net energy demand would increase, even though winter heating demand would fall. The study was limited by the way the climate change scenarios were developed. For example, it assumed that the distributions of daily, monthly, and seasonal temperatures all change consistently by the same amount. Since energy demand is affected by changes in extremes, the omission of potential changes in variability limited the study. This is obviously the case for electricity demand is concerned, since capacity is determined in part, by peak demand, and peak demand is determined, in part, by heat waves.

Minimum Temperatures

Since it is presumed that extreme minimum temperatures will be less of a problem with CO_2-induced climate change, they receive less attention here. However, changes will most likely occur in the growing areas of certain crops, where risks of frost damage, for example, may not be clearly known.

The best example of frost damage to crops is the effect of low minimum temperatures on citrus trees; this issue has been studied in depth for the citrus crop in Florida. (See Glantz, Volume X, for a discussion of the Florida citrus industry's responses to freezes in the early 1980s.) The most striking aspect of these freezes is the very short freezing time necessary for damage to occur. New citrus growth (i.e., bloom buds) can be completely killed during a 30-minute exposure to 26°F or a 3-hour exposure to 28°F. The effect of freezes is exacerbated if the crops have not hardened with the cold. Thus, if a freeze follows a warm period (i.e., indicating high daily temperature variability) when dormancy has been broken, more damage will occur at less extreme temperatures. A recent example of a freeze that affected the Florida citrus crop was the 1983 freeze, December 24-26, which resulted in a 30% reduction in citrus yield compared with the previous year (Mogil et al., 1984).

Extreme lows on a seasonal basis tend to most directly affect winter energy use for heating. The difference in heating fuel use in the United States between a warm and a cold winter can vary by as much as 400 million gallons of oil. During the extremly cold winter of 1976-77, heating degree days (calculated on a base of 65°F) were 10% greater than normal for the nation as a whole (Dare, 1981).

Precipitation

Anticipated changes in precipitation through climate change are not well known at this point. However, it is likely that geographic shifts in rainfall patterns will occur, with increases in annual total precipitation, decreases in different U.S. regions, and changes in the seasonal distribution of precipitation. Changes in the frequencies of extremes of both droughts and floods must be considered. Drought is of particular interest at the time of this writing because of the current drought in the United States and the energetic speculations being made concerning its possible connection with CO_2-induced climate change (Wilford, 1988).

Drought

The most basic definition of drought may be lack of sufficient water to meet essential needs (Gibbs, 1984). It is a condition determined relative to some long-term average condition of balance between rainfall and evapotranspiration in a particular region (Wilhite and Glantz, 1987). Different types of drought are recognized, such as meteorological drought (a departure of precipitation from normal), agricultural drought (insufficient soil moisture based on crop growth needs), or hydrological drought (based on departures from normal or relevant hydrologic parameters, such as streamflow). These "types" of drought are not completely independent, but can show up at different time lags one from the other.

Drought of any kind is anomolous as an extreme climatological event in that it is a "creeping" phenomenon; neither its onset nor its end is clearly punctuated in time. It is difficult to measure drought severity, since drought is a combination of factors: duration, intensity, and areal extent. Drought also can be one of the longer lived extreme events in that it can be measured in terms of seasons or, more frequently, years.

In the United States, major droughts have usually been defined in terms of several years, and the rate of occurrence is most strongly influenced by interannual variability of precipitation. Major drought episodes in the United States in the 20th century occurred in 1910, 1911, 1913 (serious but short lived), the 1930s (particularly 1934-36), the 1950s (1953-1957, primarily in the southern Great Plains), 1961-66 (northeastern United States), 1976-77 (primarily California and sections of the northern Great Plains), and the current drought (1988), which has been compared to drought conditions in 1936.

Although much research has been aimed at forecasting and planning for drought under the current climate (e.g., Wilhite and Glantz, 1987; Rosenberg, 1978, 1979) we still remain highly vulnerable to its impacts, as is being vividly demonstrated by current reports of agricultural disaster in areas of the northern Great Plains and forecasts of serious economic ramifications from the ongoing drought.

The effect of drought on crop production is perhaps the impact of drought that has received most research attention. The occurrence of droughts has been a major cause for yearly variability in crop production in the United States (Newman, 1978). During the 1930s, drought yields of wheat and corn in the Great Plains dropped as much as 50% below normal, whereas the drought in the 1950s brought less dramatic declines in yields (Warrick et al., 1975). The reduction in vegetative cover associated with drought also brings about severe soil erosion, which will diminish future crop productivity. Low yields of forage crops result in inadequate food for livestock and premature selling off of livestock.

Soil moisture deficits affect natural vegetation as well as crops. Again, much of the research in natural ecosystems has been on forests. Soloman and West (1985) identify drought as the cause for death of seedlings and for slowed or stopped growth of mature trees.

Aside from the direct effects of insufficient moisture on unmanaged ecosystems, indirect effects also result from increased incidence of fires. In the Australian drought of 1982-83, for example, brush fires destroyed over 8,000 km^2 of land; most of this area was forested (Gibbs, 1984). During the drought of 1988, forest fires have broken out across the country.

The effects of drought on U.S. energy resources are most obvious with regard to the generation of hydroelectric power. In the study described above on the impacts of climate change on electric utilities (Linder et al., 1987), the effect of decreased streamflow due to drought on the production of hydroelectric power in New York was discussed. In New York, 25% of electricity is supplied by hydrogeneration, mainly from the Niagara and St. Lawrence projects. Historical fluctuations have been extreme at times, as seen in 1964 during the northeastern drought when the Niagara Project generated 36% less energy than normal (Linder et al., 1987). Other regions of the country are even more dependent on hydrogeneration of electricity. Two-thirds of the total electricity in the Pacific Northwest is generated by hydropower. In this region, large variations in energy capacity result from variability in precipitation (Northwest Power Planning Council, 1983).

Floods

On average, 200 people die each year from flooding; flash floods account for most of these deaths (AMS, 1985). Floods also destroy property, crops, and natural vegetation, and disrupt organized social systems.

Floods result from a combination of meteorological extremes (heavy precipitation from severe storms, such as hurricanes and thunderstorms), the physical characteristics of particular drainage basins, and modifications in drainage basin characteristics made by urban development. Loss of life and property is increasing as use of vulnerable floodplains increases.

The recurrence interval of flooding is most important in applying effective control and protection mechanisms. These include building dams, reservoirs, and levees, and improving channels and floodways (White et al., 1975). For example, flood control reservoirs are designed to operate at a certain level of reliability, and the reliability is determined by a certain flood magnitude that the reservoir can handle, such as a 100-year flood.[*] Hence, the statistics of flooding are key for designing for protection and are based on a certain climatic variability determined from the historical record. As that variability changes, the reliability of the protection system will change.

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[*] A 100-year flood is a flood of a certain magnitude specific to a drainage basis, which has a 1% probability of occurring in a year.

This is currently seen in systems where longer precipitation and streamflow records change the recurrence interval of particular magnitudes of flooding, such as in the case of Folsom Dam in northern California (Reibsame, 1987). Overtopping of dams accounted for 33% of total flood loss during 1903-58. During 1900-79, 26% of dam failures were due to overtopping (Clark, 1987). In 1972, overtopping of levees accounted for at least 40% of losses from tropical storm Agnes, which was one of the largest natural catastrophes in terms of property damage. With changing variability in climate, overtopping could become more common, and losses from floods could increase.

Major recent floods include the following: (1) Rapid City, South Dakota (June 1972), 231 deaths, more than $100 million in damage; (2) northeastern United States (June 1972), 120 deaths and about $4 billion damage -- inundation from hurricane Agnes; (3) Big Thompson Canyon, Colorado (July 1976), 139 deaths, $50 million in damage -- a result of a stalled thunderstorm system that delivered 12 inches of rain in less than 6 hours (Henz and Sheetz, 1976); (4) Johnstown, Pennsylvania (July 1977), 76 deaths and $200 million in property damage -- a result of slowly moving thunderstorms that deposited 11 inches of rain in 9 hours.

Floods in the 1980s have been less serious in terms of loss of life, but changing frequencies of severe storms, such as thunderstorms and hurricanes as well as general shifting of precipitation patterns could result in unprecedented losses from floods in a climate-changed world.

Severe Storms - Hurricanes

Three important kinds of climatic extremes are present in hurricanes: strong winds, intense and high precipitation amounts, and extreme storm surges. A hurricane is an extreme form of a tropical cyclone, characterized by torrential rains, typically as much as 5 to 10 inches in one storm; high windspeeds, which can exceed 100 mph; very steep pressure gradients, with pressure at the center as low as 915 millibars (mb) and with diameters of 100 to 400 miles.

The deadliest hurricane to hit the United States was the Galveston hurricane of 1900, which killed 6,000 people. However, the deadliest hurricane worldwide struck Bangladesh in 1970, resulting in 300,000 deaths. Hurricane Agnes in 1972 caused over $4 billion in damages to Florida and the northeastern United States. (Much of this damage resulted from flooding inland in the Northeast. Damages from high winds and surges were confined to coastal areas.) Hence, the frequency and intensity of hurricanes is of major concern for the inhabitants of U.S. regions where they commonly occur -- i.e., the gulf and the South Atlantic coasts.

Hurricanes are classified according to their severity on the Saffir/Simpson Scale (1-5), taking into account the central pressure, windspeed, and surge. Major hurricanes are considered all those of categories 3-5 wherein central pressure is less than 945 mb, windspeeds exceed 110 mph, and the surge is greater than 8 feet (Herbert and Taylor, 1979).

From 1900 through 1978, 53 major hurricanes (categories 3-5) directly hit the United States (averaging two major hurricanes every 3 years). Overall, 129 hurricanes of any strength hit the United States, which averages to approximately two per year. In recent decades, the number of major hurricanes has declined. From 1970 to 1978, only three hurricanes occurred compared with six or more in earlier decades. The last hurricane of category 4 or 5 to strike the United States was hurricane Camille in 1969. (Hurricane Allen (1980), which at one time reached force 5, weakened before it struck a relatively unpopulated segment of the Texas coast (Oliver, 1981).) Since then, the population of the south coastal regions of the United States has grown tremendously, and most inhabitants have never experienced a major force hurricane. Building in coastal areas has also increased with population, which raises the potential for high property damage. Thus, the population may be more vulnerable and less prepared to handle this particularly devastating extreme event (Sanders, 1982). Any increase in the frequency and/or intensity of these storms, which could result from climate change, would be of great concern to south coastal regions of the United States.

Coleman (1988) has found some limited evidence for increased frequency on the basis of examining the historical record for the number of storms formed in the North Atlantic during years of warmer than average sea surface temperatures. Emmanuel (1988a) has found through a hurricane modify experiment that the intensity of hurricanes increase under warmer conditions. The extreme intensity of Hurricane Albert this past summer is consistent with the findings. Emmanuel (1988b) also asserts the importance of establishing a general theory of hurricane development independent of current atmospheric conditions, so that scientists can predict changes in frequency and intensity of storms with climate change.

PRIOR STUDIES ON THE MODELING OF CLIMATE VARIABILITY

Studies comparing variability statistics of observed time series with variability statistics of general circulation model (GCM)-generated time series of climate variables relevant to climate impacts are not numerous in the atmospheric sciences literature, although studies first appeared in the early 1980s (e.g., Manabe and Hahn, 1981; Chervin, 1981). Such studies are critical if climate change research is to determine if the variability statistics of doubled CO_2 experiments with GCMs are valid. To accomplish this, the ability of GCMs to reproduce the variablity statistics of the present-day climate must be examined, and a thorough understanding of descrepancies attained. Five of the more recent and relevent works that address comparison of variability are briefly reviewed in this section. Very often, these studies also involve a study of the change in variability under doubled CO_2 conditions.

Chervin (1986) investigated interannual climate variability and climate prediction. He designed a special version of the NCAR, CCMO (National Center for Atmospheric Research Community Climate Model) to eliminate external variability of interannual time series of climate variables, so that discrepancies between modeled and observed variability would reflect the external component of variability present in the observed data. The additional variability attributed to external boundary conditions is considered the potential predictability of the climate. The model was modified such that external boundary conditions remained the same each year of the 20-year model run. This entailed the prescription of monthly sea surface temperatures and sea ice distributions. The variability of mean sea level pressure and 700-mb geopotential height (which is related to large-scale wind patterns) were analyzed in the Northern hemisphere, with particular focus on the United States. Results indicated no significant differences between modeled and observed variabilities of mean sea level pressure over the United States and only limited areas of differences in the variability of 700-mb geopotential height. It should be noted, however, that these results are based on the assumption that processes responsible for the internal variation of the atmosphere are correctly incorporated in the model.

Bates and Meehl (1986) also used the CCM to investigate changes in the frequency of blocking events on a global scale under doubled CO_2 conditions. Their version of the CCM included a seasonal cycle, computed hydrology, and a simple mixed layer ocean. The statistics of the 500-mb height field (the height above the surface at which atmospheric pressure equals 500 mb) are examined, as are blocking events defined as persistent positive height anomalies (which indicate high pressure). Blocking events are strongly related to persistent surface temperature anomalies, such as heat waves in the summer. Hence, changes in the frequencies of blocking events have significant implications for changes in the frequencies of extreme temperature events. In comparing modeled data with observed data for a 10-year period, they found that the model does a "reasonable" job of simulating 500-mb height standard deviations, particularly in winter in both hemispheres. The model, however, produces too few extreme blocking events. Under doubled CO_2 conditions, standard deviations of 500-mb height and blocking activity were found to decrease in all seasons (i.e., the variability of blocking events decreased).

Two studies were recently conducted on local or regional scales using the U.K. Meterological Office 5-layer GCM. Reed (1986) analyzed observed versus model control run results for one gridpoint in eastern England, and addressed the problem of creating the correspondence between the model grid square and the spatial average of several observation points. He analyzed the mean and variance of temperature for a 3-year integration of model runs. Compared to observations, the model tended to produce temperatures that were too cool and variability that was too high as measured by the standard deviation. For precipitation, the model produced too many rain days but did not successfully simulate extreme rain events of greater than 20 mm/day.

Most recently, Wilson and Mitchell (1987) examined the modeled distribution of extreme daily climate events over Western Europe, using the same model. Comparisons were made of minimum surface temperatures and precipitation. Again, the model produced temperatures that were too cold, and hence, extreme minimum temperatures were overestimated. This problem was most pronounced in grid boxes away from the coasts. The model also produces too much precipitation in general, but does not successfully reproduce observed highest daily totals. The number of rain days is overestimated. Wilson and Mitchell examined changes under qradrupled CO_2 conditions and found that variability of temperature generally decreased, which given the general warming, indicates a marked reduction in the occurrence of freezing temperatures. The authors compared the changes in intra-annual temperature variability using the more rigorous procedures of Katz (1984) as well as using the more standard F-test. Both tests indicate a signicant decrease in winter temperature variability. The authors emphasized the importance of examining variables of importance to climate impact analysis, but also of using a model that faithfully reproduces the present-day climate in terms of means and extremes.

Hansen et al. (1988) used the GISS model II general circulation model to simulate the global climate effects of time-dependent variations of atmospheric trace gases and aerosols. Several different scenarios of trace gas increase from 1958 to the present were used. A one hundred year control run was also produced. From this run it was determined that globally the model only slightly underestimates the observed interannual variability. However, the model's variability tends to be larger than observed over land. Among the calculations made with output from the transient (i.e. progressive climate change) run were changes in the frequencies of extreme temperature events. This was accomplished by adding the change in temperature with climate warming predicted by the model to observed local daily temperatures. Hence the authors assumed no change in variability in making these calculations. Results indicate that predicted changes in the frequency of extremes beyond the 1900s at such locations as New York, Washington, and Memphis, become quite large, and would have serious impacts.

The studies reviewed above indicate some important shortcomings of GCMs with regard to their ability to faithfully reproduce observed variability statistics. More research is clearly needed to further determine the sensitivity of the models to changes in physics, resolution, and so forth, with regard to the determination of variability. Moreover, only one of these studies explicitly concerns variables of importance to climate impact analysis. Studying the higher moments (e.g. variance) of climate variable statistics, and carefully verifying the models' ability to reproduce observed variability on regional scales, are the necessary prerequisites to rigorously analyzing possible changes in these statistics under doubled CO_2 conditions.

STUDIES FOR THIS REPORT

Two research efforts were undertaken for this report to attempt to increase knowledge concerning how climate variability will change. The climate change scenarios for use in the climate change impact studies reviewed in this report excluded consideration of changes in variability (see Chapter 3). The following two studies on GCM estimates of current and future variability were performed for this report:

1. Variability and the GISS Model - Rind, Goldberg, and Ruedy, Goddard Institute for Space Studies.

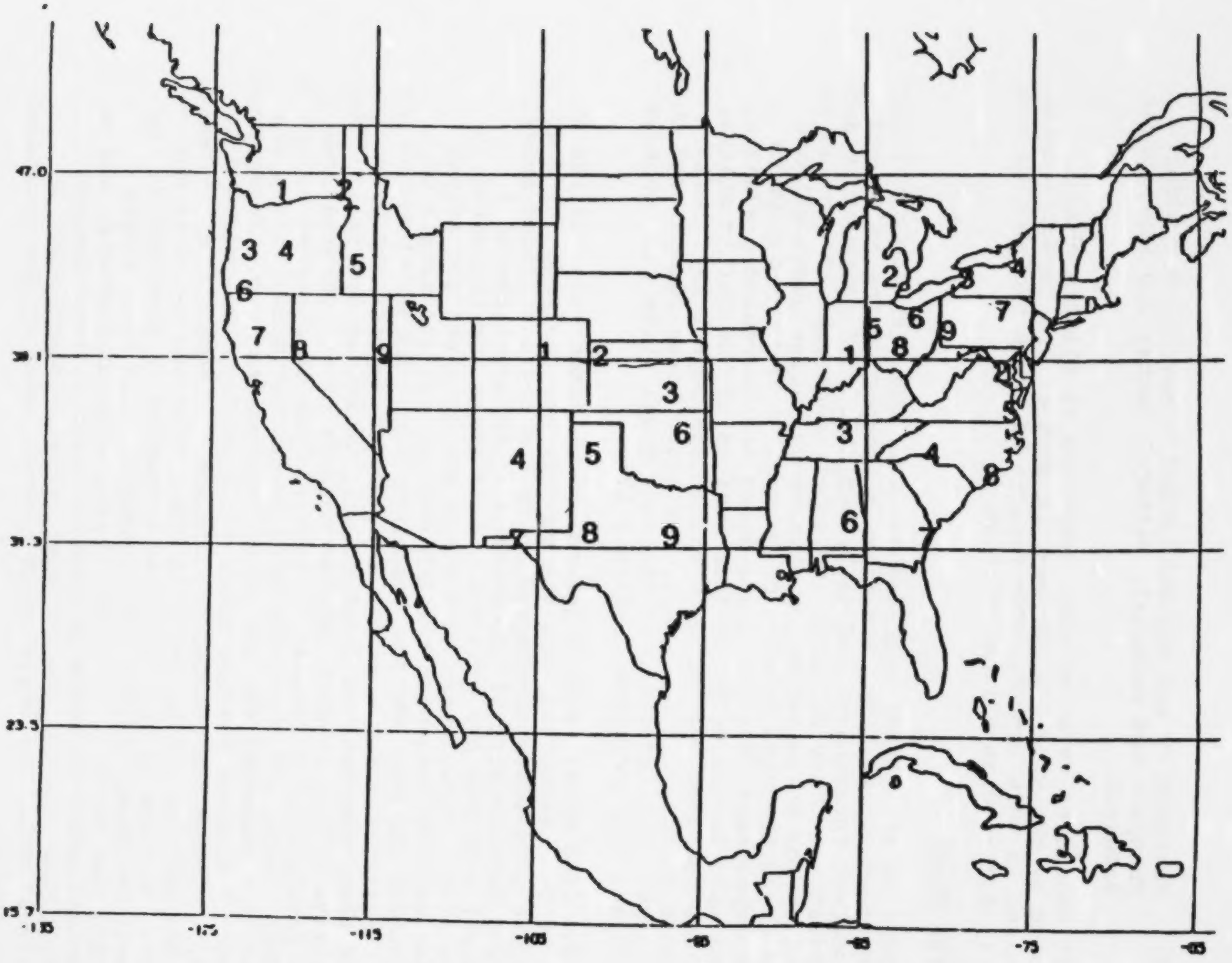
2. Variability and the NCAR Model - Mearns, Schneider, Thompson and McDaniel, National Center for Atmospheric Research.

It should be recalled that scenarios of climate change generated by the GISS GCM are used in most of the impact studies summarized in this report. The results of these two studies are directly compared in a later section.

The GISS Study

Rind et al. (1988) examined how well the GISS GCM simulates the observed variability of climate by comparing the model and the observed interannual and daily variations of temperature and precipitation. They describe the model assessment of changes in variability of these two major climate variables under climate change using the GISS doubled CO_2 run and a transient climate change experiment in which trace gases are increased gradually. The analysis is conducted in four regions of the United States, which are the four regions upon which this report is focused: the Great Plains, the Southeast, the Great Lakes region, and the West Coast. The locations of the four model grids representing these areas are indicated in Figure 17-1.

The GISS model, a grid general circulation mode, is run at the 8 by 10° resolution, and the results are analyzed for four different grid boxes corresponding to the regions listed above. Observed data consist of the average of observations at 9 different stations per grid box. Grid boxes are indicated in Figure 17-1. First, mean conditions are compared for actual weather observations with the GCM control run (or single CO_2), the doubled CO_2 run, and the transient run. The model values for mean temperatures for 4 months in the four regions are generally cooler than observations (particularly in summer and fall), they are always within several degrees Celsius of the observations. Model precipitation values are fairly close to observed values in the Great Lakes and Southeast grid boxes, but model values are higher than observed for the other two regions (e.g., January in the southern Great Plains: model = 2.1 mm/day, observed = 0.46 mm/day). Under the doubled CO_2 scenarios, temperatures increase over the control run by 4-6°C in the winter and 3-4°C in the summer. Warming in the transient scenarios is progressive, but temperature change occurs more gradually than with simply doubling the CO_2 amount. Winter warms more than summer, and so the annual seasonal cycle is reduced under climate change. Precipitation changes are not statistically significant at individual grid, but there is an overall tendency for increased precipitation.


47.0
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15.7
-135
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Figure 17-1. The Locations of the Four Model Grids.

Interannual Variability

Standard deviations of temperature and precipitation of observed and modeled data were compared for all months. In most months, the model year to year temperature variability is similar to the observed variability in the four regions, but in summer the variability was overestimated by 0.3-0.6°C. Precipitation variability is overestimated in half of the cases where precipitation amount is also overestimated. The relative annual variability of precipitation (that is the standard deviation relative to the mean) of the model is generally in agreement with observations.

Under conditions of climate change (doubled CO_2) in comparing control versus climate change interannual standard deviations (a sample size of 10 years in each case) for each month in all regions, there is generally reduced variability of temperature from January through April. (These results were further substantiated by examining the changed variability at other tropical grid boxes in the United States.) Results for other seasons of the year are more ambiguous. For precipitation, the doubled CO_2 climate resulted in increased variability in most months at the four grids (in 31 of 48 cases), but was particularly striking at the southeast grid. These changes, however, were often of the same order as the model's natural variability (from examination of the 100-year control run). The sign of the change in mean value and the sign of change in interannual variability are highly correlated.

Daily Variability

Daily variability of temperature was analyzed by taking the daily departures from monthly means and comparing the resulting model distribution with the distribution formed in the same manner from the observational data. Two statistical tests were used.

Ten years of control run for the transient experiment for 4 months (January, April, July, and October) were compared with 30 years of observations. Distributions of observed versus model daily temperature data were, in general, not significantly different. Comparisons were also made by calculating the standard deviations of the departures from the mean for the four months (Table 17-1a). These results indicate that the model's values are significantly greater than the observed, which demonstrates that the model is producing too many extremes.

Table 17-1a. Daily Temperature Standard Deviations (°C) (Rind et al.)

Month	Location	Observed SD	Current SD	2010s SD	2030s SD	2060 SD
January	Southern Great Plains	4.81	8.15	0.61	-1.19	-0.83
	Southeast	4.53	6.90	-0.14	-1.14	-0.23
	West Coast	3.63	5.86	-0.61	0.05	-0.16
	Great Lakes	4.97	5.79	0.44	-0.33	-0.44
April	Southern Great Plains	3.72	5.77	-0.57	-0.27	-0.80
	Southeast	3.71	5.50	-0.65	-1.61	-1.24
	West Coast	2.59	4.29	0.77	0.60	0.33
	Great Lakes	4.65	6.15	-0.51	-0.26	-1.39
July	Southern Great Plains	1.74	2.56	0.54	-0.19	0.18
	Southeast	1.50	2.34	0.14	-0.22	-0.24
	West Coast	2.40	3.56	0.03	0.54	0.28
	Great Lakes	2.38	3.02	-0.48	-0.84	-0.14
October	Southern Great Plains	3.79	5.16	1.16	0.97	1.35
	Southeast	3.59	5.21	-0.54	-0.25	-0.73
	West Coast	3.15	6.51	-0.55	-0.30	-0.80
	Great Lakes	4.09	5.46	-0.37	0.91	-0.06

Under climate change, comparing temperature distributions of the control run with a series of decades from the transient experiment reveals that the distributions did not significantly differ. Results comparing standard deviations (presented in Table 17-1a) indicate that, although changes with time are not strictly progressive, most cases by the end of the climate change experiment show reductions in the standard deviation (although these reductions are not statistically significant). Hence, a decrease of daily temperature variability is not demonstrated by these results.

For precipitation, comparisons are more complex. For example, the number of observation stations used to represent a grid box does affect the results. Model rainfall distributions differ significantly from observed in half of the cases (in three seasons for the West Coast and the southern Great Plains). The model also produces less days of light rain in general and more extreme values in the winter in all four regions. These results are also confirmed by comparison of standard deviations (Table 17-1b).

As the climate warms, again considering the various decades of the transient experiment, the precipitation distributions differ from the control climate in about one-fourth of the time with no general progression over the decades. Figure 17-2 presents a sample set of distributions for precipitation during several decades of warming for the West Coast in April. In comparing standard deviations (Table 17-1b), in half of the cases, the warmest time period exhibits increases in standard deviations. These results are again consistent with those for interannual variability.

Variability of the Diurnal Cycle

It would be expected that the diurnal cycle would decrease under changed climate as the additional greenhouse gases could limit nighttime cooling. Comparisons of control model results with observations are reasonable in the four regions. Under doubled CO_2 conditions, it was found that the amplitude of the diurnal cycle very definitely decreases in summer but changes inconsistently in the other seasons. The reason for this is the dominance of radiative heating in the summer and of other forms of heating and cloud cover change in other seasons.

Table 17-1b. Daily Precipitation Standard Deviations (mm d^{-1}) (Rind et al.)

Month	Location	Observed SD	Current SD	2010s SD	2030s SD	2060 SD
January	Southern Great Plains	1.08	2.80	0.05	0.05	1.68
	Southeast	4.35	4.62	-1.20	-1.35	-0.85
	West Coast	3.23	4.55	-0.18	0.34	0.13
	Great Lakes	2.23	4.06	-1.07	-0.94	-0.50
April	Southern Great Plains	2.51	3.26	0.94	1.99	1.17
	Southeast	4.35	3.85	0.95	-0.15	0.81
	West Coast	1.41	2.76	0.07	1.02	-0.12
	Great Lakes	3.85	3.29	-0.43	-0.31	0.44
July	Southern Great Plains	2.79	3.08	-0.10	-0.09	0.36
	Southeast	4.13	3.31	0.28	0.29	0.11
	West Coast	0.57	1.53	0.44	0.24	0.71
	Great Lakes	3.68	2.48	-0.06	0.72	0.35
October	Southern Great Plains	2.75	1.79	0.52	0.34	0.00
	Southeast	3.77	3.88	0.72	-0.15	-0.28
	West Coast	1.86	2.69	1.20	-0.63	1.34
	Great Lakes	3.58	2.26	0.52	0.76	0.95

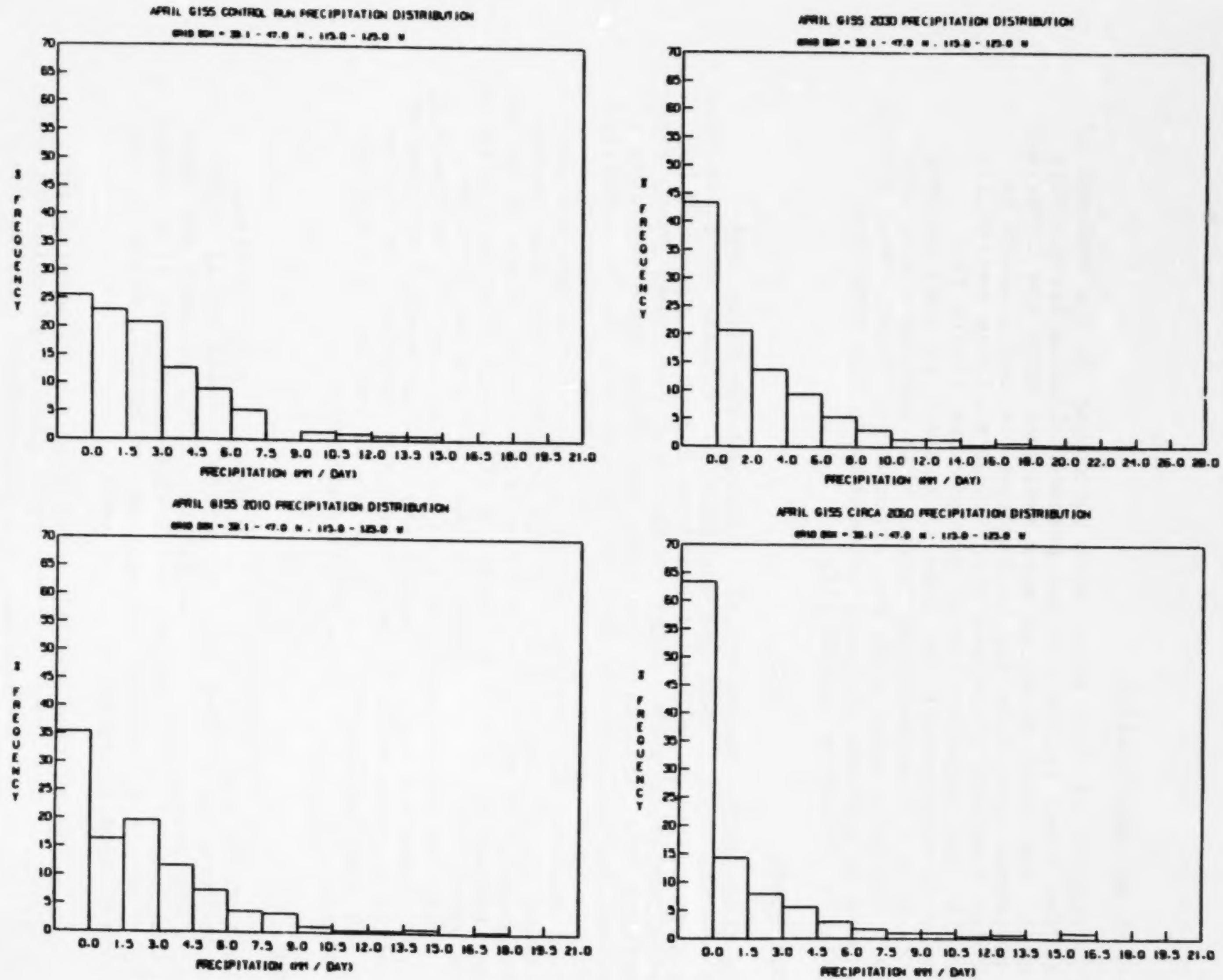

Figure 17-2. Sample Set of Distributions

Source: Rind et al., Volume _.

Discussion and Conclusions

The results of this study must be viewed in the context of how well the model reproduces the present climate variability. In general, the model produces more extremes than are observed. It is suggested that this may be because the model fails to account for feedback processes that would minimize variability. For example, the conservation of groundwater limits the occurrence of temperature extremes in summer, as some surface energy is used for evaporation rather than heating the ground surface. The GISS model does not account for this. This points to the need to include physical processes in the GCMs that particularly influence variability.

The NCAR Study

In this study, Mearns et al. analyzed the first and second moments (i.e., mean and variance) of climate variable time series from selected empirical stations and those produced by general circulation model (GCM) control and perturbed runs, first to determine how faithfully the GCMs reproduce these measures of the present variability and then to examine how the variability will change in CO_2 perturbed cases. This type of research is essential because the variability performance of a GCM not only is relevant to the credibility of its forecasts but also serves as a diagnostic of the validity of model physics, since it is the physical processes within the model's structure that give rise to climate variability. By comparing the relative performance (i.e., model versus observations) of various versions of the NCAR CCM (i.e., versions with different physical parameterizations or formulations), they help to determine what formulations may be needed for forecasting certain measures of variability and how much credibility to assign to those forecasts.

Methods

This study used the output from control runs of three different versions of the NCAR Community Climate Model (CCM). However, the version of Chervin (1986) is the primary one used for comparison of observed and model control output (i.e.,model runs to simulate the actual present-day climate), since it has the longest time integration (20 years).

The version of the CCMO(A) model used is documented in Chervin (1986). The CCMO is a spectral general circulation model originally developed by Bourke and collaborators (Bourke, 1974; Bourke et al., 1977), which has been modified by the incorporation of radiation and cloud parameaterization schemes.

The model has a resolution for physical processes of approximately 4.5° in latitude and 7.5° in longitude, and has nine levels in the vertical. This version includes an annual solar cycle featuring identical, seasonally varying forcing each year. Identical forcing each year was accomplished by prescribing for each month ocean surface temperatures and sea ice distributions.

The other two versions of the CCM used are the Washington version of the CCMO(A) (Washington and Meehl, 1984), which includes an interactive thermodynamic ocean and surface hydrology, and the Dickinson version (Dickinson et al., 1986), a version of the more sophisticated CCM1(B) containing a diurnal cycle and a very sophisticated land surface package, the Biosphere-Atmosphere Transfer Scheme (BATS).

The same four regions of the United States were chosen for investigation as were chosen for the GISS study: the Great Plains (represented by three grid boxes), the Southeast, the Great Lakes and the West Coast. The locations of the grid boxes are indicated on Figure 17-3. Note that the NCAR model grids for the Great Plains are further north than the GISS grid for the southern Great Plains.

Real data corresponding to each grid box were generated from the average of six observation stations for time series of temperature and precipitation. Solar radiation and relative humidity real data were taken from one Solmet observation station located in each grid square. Figure 17-3 shows the location of all observation stations and grid boxes.

Four variables deemed particularly relevant to climate impact analysis were chosen for this analysis: daily mean temperature, daily total precipitation, mean daily relative humidity, and mean daily absorbed solar radiation.

Comparison of Observed versus Chervin Control Run

Temperature

Figure 17-4 displays the time series of daily average temperature for modeled and observed data for the four regions investigated. The model successfully simulates the annual cycle for the four regions, which represents the variability within the year. There are regional differences, however. In the Great Plains region, the model annual range is slightly smaller than that of the observed time series (Figure 17-4a), whereas in the Great Lakes region (Figure 17-4b) the model annual range is

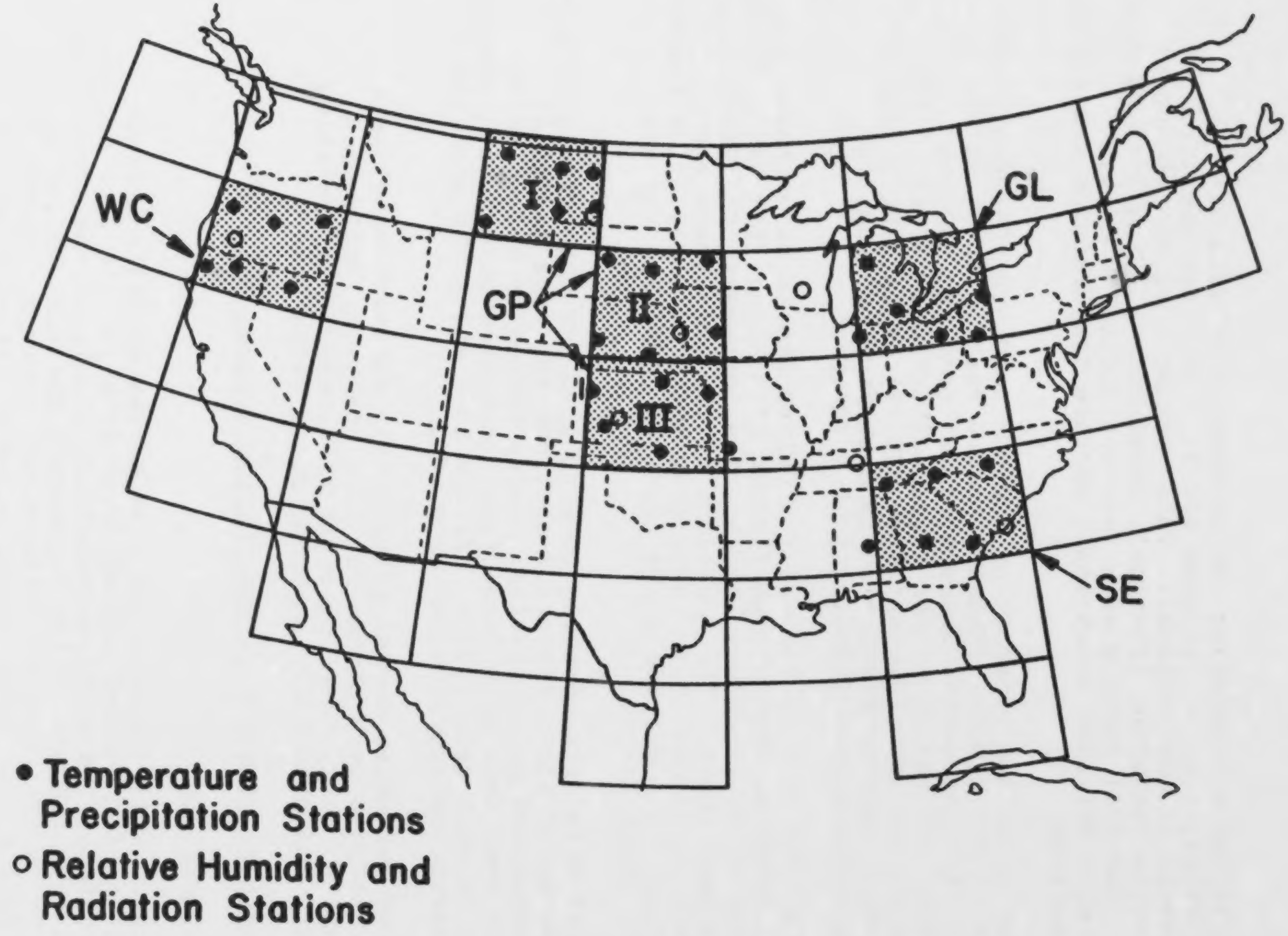
WC
I
GP
II
III
GL
SE
● Temperature and Precipitation Stations
○ Relative Humidity and Radiation Stations

Figure 17-3. Model Grid Cells and Station Locations.

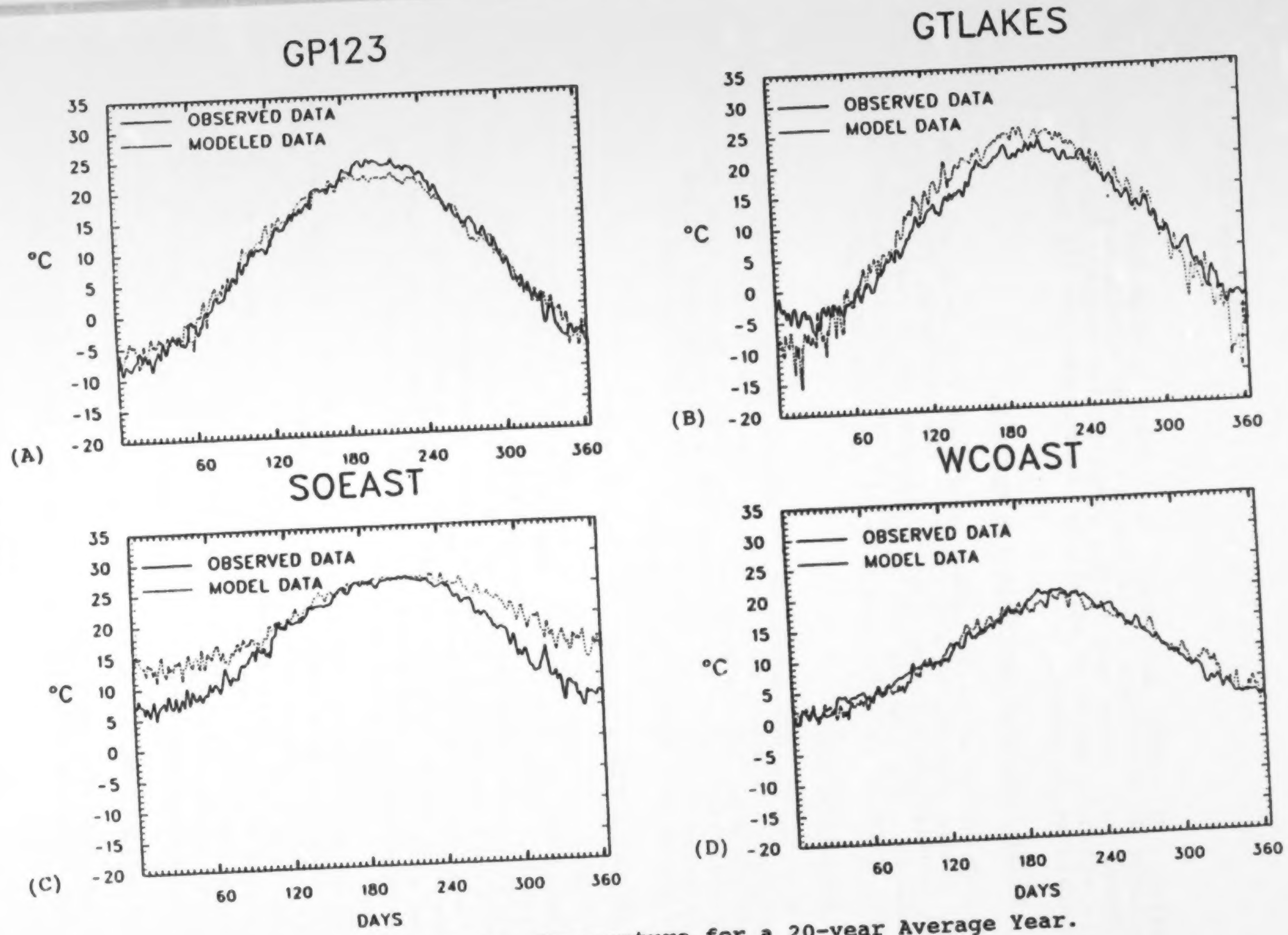

Figure 17-4. Average Temperature for a 20-year Average Year.

Source: Mearns, et al., Volume _.

greater. The least successful simulation is that for the Southeast grid (figure 17-4c), where winter minima are too high by about 8°C. Note that in the Great Plains region, the model falls slightly short of attaining the appropriate maximum temperatures in summer.

Solar Radiation and Relative Humidity

Simulation of solar radiation ranges from very good (the Great Plains region) to only fair at the Southeast where the model consistently overestimated absorbed solar radiation during all months. The Chervin CCM is strikingly poor at simulating the annual cycle of relative humidity at all four locations.

Precipitation

The Chervin CCM consistently overestimates precipitation, although the seasonal cycle is well simulated in the Great Plains region and the West Coast grid. The authors do not know why the model overestimates precipitation but speculate that it may partially be a result of a precipitation parameterization criterion of 80% relative humidity.

Variability Comparisons of the Chervin CCM

Interannual variability of temperature is generally underestimated by the Chervin CCM in all four regions. Interannual variability of precipitation (i.e., relative variability, the standard deviation relative to the mean) is generally in reasonable agreement with observed data, although it is occasionally overestimated. This is a particularly encouraging result for the credibility of predicting climate changes given how inaccurate the control precipitation results are in terms of absolute values.

In terms of daily variance, model relative humidity tends to be much less variable than observed values at all locations and in most months. Results for temperature for January and July indicate that the Chervin model generally overestimates daily temperature variance (on the basis of statistical tests on the innovation variance, i.e., the variance that remains when the effect of autocorrelation is removed). Solar radiation daily variance comparisons are not particularly interesting.

Intercomparisons of Three CCM Versions and Observed Data

Given that all GCMs fail in certain respects to accurately reproduce observed climate, Mearns et al. felt that it would be useful to compare different model versions' simulations of present-day climate to be aware of the possible ranges of errors and to understand more fully the effect of model structural differences. The present-day climate runs of models incorporating physics different from those of the CCMO(A) version of Chervin (1986) investigated in the third section are compared. Both the Washington and Dickinson runs consist of 3-year integrations. Table 17-2 presents comparisons of annual and seasonal mean conditions simulated by the three models and observations for the Southeast (SE) grid. Statistics of interannual variability cannot be analyzed because there are too few years of simulated data.

There is considerable variability in how well the models reproduce mean total precipitation for the SE grid, ranging from the very good results of Dickinson's model, to the overestimation of Chervin's model, the underestimation of Washington's model. On the basis of mean annual and seasonal comparisons, no one model is clearly superior to the other two in accurately reproducing mean climate at the four locations.

The Dickinson model also produced much lower daily variability of temperature than the other two models or in some cases, than the observations. This result is graphically illustrated in the temperature histograms (three models and observed) for two key months for the SE grid (Figure 17-5).

The reasons for these discrepancies have yet to be explored in depth, but are likely related to different land surface packages in the models. A possible explanation for the lowered daily temperature variability of the Dickinson model concerns the more sophisticated surface energy balance used, which includes consideration of soil heat capacity.

Control versus CO_2 Perturbed Runs

The authors included a preliminary analysis of changes in precipitation and temperature, under a scenario of doubled CO_2, using the output from Washington's control and doubled CO_2 runs for the four regions. Interannual variability could not be analyzed because the time series are too short. However, examination of daily variance of temperature is presented.

Table 17-2. Southeast Grid -- Multicomparisons of CCM Model Version and Observed Mean Temperature and Total Precipitation Statistics (Mearns et al.)

	Obs.	Chervin	Wash.	Dick.
Annual				
Mean T (°C)	16.6	20.0	20.1	21.5
Total precipitation (mm)	1137.2	3085.5	589.1	1401.8
Winter				
Mean T (°C)	7.4	14.1	14.8	16.0
Total precipitation (mm)	738.9	295.3	393.4	293.2
Summer				
Mean T (°C)	25.5	25.9	24.2	26.6
Total precipitation (mm)	317.0	786.4	75.7	346.9

Obs. = Observations.
Chervin = Chervin CCM version (20-year run).
Wash. = Washington CCM version (3-year run).
Dick. = Dickinson CCM version (3-year run).

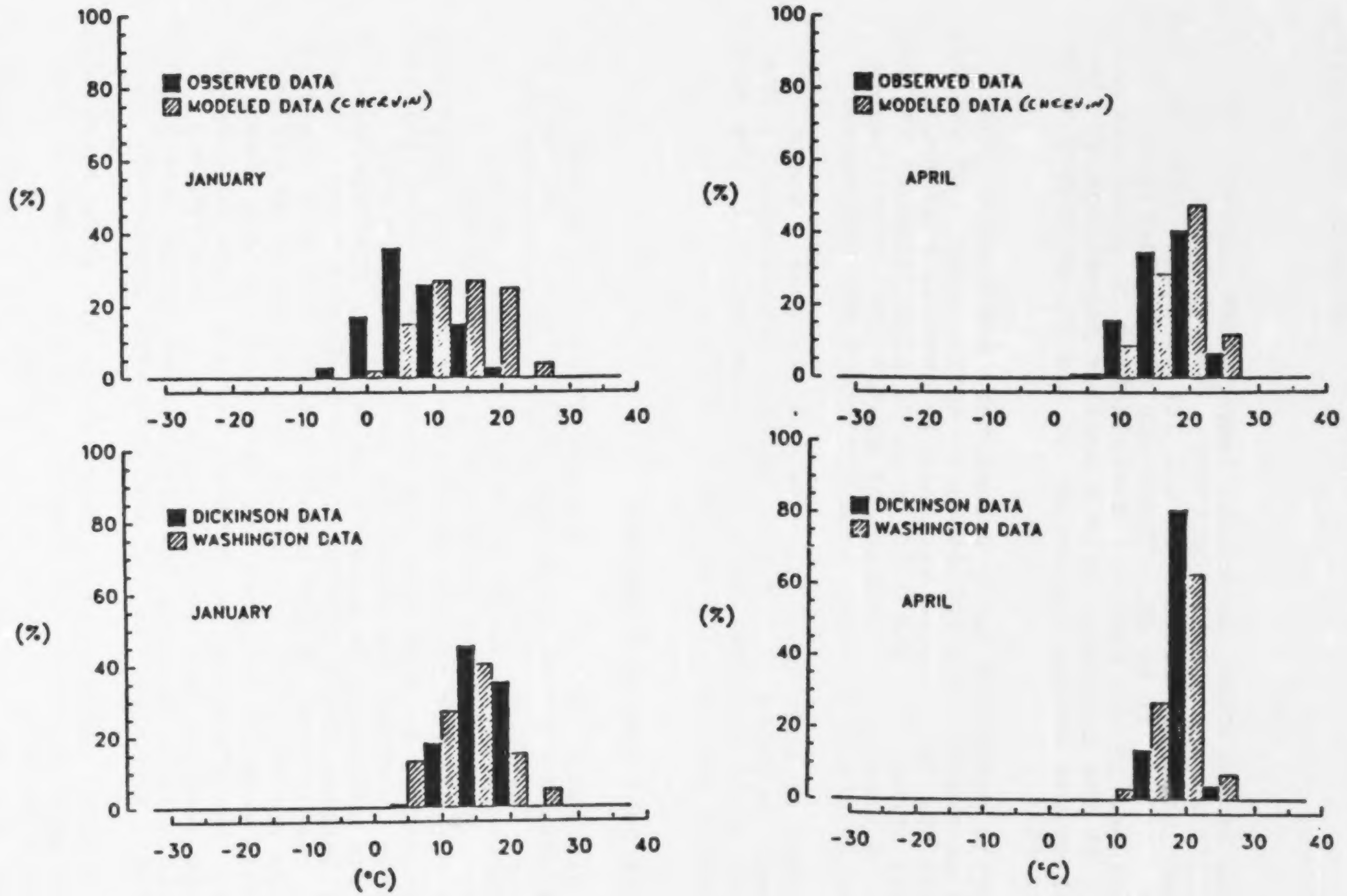

Figure 17-5. The percentage of events for the intervals ± 2.5°C from the given temperature.

Source: Mearns et al., Volume _.

As would be expected, an annual temperature increase of about 2 and 3°C occurs at all locations. Annual total precipitation increases between 22 and 26% at three locations but decreases slightly (2%) at SE. There are also potentially important changes in the seasonal distribution of precipitation. For example, at the Southeast grid a smaller percentage of the annual total occurs during the summer in the CO_2 perturbed case (from 13% to 6%).

Statistics comparing daily temperature variance of the control and perturbed runs for January, April, July, and October indicate that the temperature variance in general does not significantly change (at the 0.05 level of significance) at these four grids. Without consideration of statistical significance levels, results are mixed with both increases and decreases.

Percentage of rain days decreases in the summer under climate change in three of the four grids. Interestingly, the occurrence of small precipitation amounts decreases in the summer in the perturbed case for the Southeast grid.

COMPARISON OF GISS AND NCAR RESULTS

It is difficult to compare the two studies. The modeling experiments were conducted partially with different purposes in mind using two different models (which differ not only in how physical processes are modeled but also in their spatial resolutions). They also use different qualitative and statistical methods for making comparisons. The GISS experiment was aimed primarily at examining the changes in variability with climate change, whereas the immediate purpose of the NCAR experiment was primarily to examine and explain discrepancies in variability between model control runs and observations. Since the spatial resolutions of the models differ, the grid boxes of the models do not coincide and so the regions analyzed differ. These are only some of the problems that would affect these comparisons. Nevertheless, an attempt is made here to compare some of their results that roughly coincide. Some regions coincide fairly well (such as the Great Lakes grids, see Figures 17-1 and 17-3), and some similar analyses were conducted.

First a brief comparison is made of how the models reproduce the observed mean climate. In general, the GISS model is too cool and the NCAR model(s) too warm. Precipitation is overestimated at two grids by the GISS model and is overestimated at all grid boxes by the Chervin version of the NCAR model (although this is not true of two other versions of the NCAR CCM).

The following sections compare the observed and control runs of interannual and daily variability of temperature and precipitation, and then comparisons of climate change variabilities are made. It must be emphasized again that comparison of control runs with observed data is an essential step in the process of trying to evaluate the models' forecasts of climate change.

Interannual Variability

The easiest and most straightforward comparison can be made of the two studies' results for interannual variability of temperature and precipitation control runs. Relative variability values (standard deviation relative to the mean) for the GISS study were provided by its authors (Rind, personal communication). Rind et al. use a 100-year control run for interannual variability calculations. Their observational data set consists of 30 years (1951-80). The NCAR study uses a 20-year control run of Chervin (1986) and a 20-year observational data set (1949-68). The differences in sample size should be noted. Table 17-3a and 17-3b present the relevant results, winter and summer standard deviations for temperature, and annual coefficients of variation (i.e., a measure of relative variability) for precipitation for the four regions for both studies. The overlap for the GISS southern Great Plains grid box and the NCAR Great Plains III grid (see Figures 17-1 and 17-3) is considerably less than in the case of the other three regions (Great Lakes, Southeast, and West Coast). In comparing the model temperature standard deviations with the observed for each study, there is little agreement in the direction of error from model to observed. Both models overestimate the variability of the Great Plains region in winter. (However, the difference in the NCAR study was deemed statistically insignificant.) Both models underestimate the temperature variability (but the NCAR model much more so than the GISS) for the West Coast winter. In all cases the GISS study shows an overestimate and the NCAR study an underestimate by the model, of variability.

Regarding the relative variability of precipitation, the results for the two models are rather similar, although the GISS values tend to be absolutely higher. The differences between observed and model values are very close (from 1 to 6 percentage points) in each study. The NCAR model slightly underestimates the variability at each location, whereas the slight errors in the GISS results are mixed.

Table 17-3. Interannual Standard Deviations. Temperature and Precipitation, GISS and NCAR Control Runs (Rind, personal communication and Mearns et al.)

		Temperature (°C)		Precipitation
		Dec.-Feb.	June-Aug.	Annual (%)
a. GISS (n = 100)				
SGP	Model	1.65	1.05	15
	Obs	1.20	0.75	21
SE	Model	1.65	1.05	22
	Obs	1.65	0.70	18
WC	Model	1.35	1.35	18
	Obs	1.45	0.75	23
GL	Model	1.35	1.25	18
	Obs	1.50	0.70	18
b. NCAR (n = 20)				
GP III	Model	1.3	0.14	17
	Obs	1.1	1.2	22
SE	Model	1.0	0.38	10
	Obs	1.8	0.74	12
WC	Model	2.2	0.71	10
	Obs	1.6	0.88	11
GL	Model	0.8	0.17	17
	Obs	1.45	0.81	17

SGP = Southern Great Plains; SE = Southeast; WC = West Coast; GL = Great Lakes.

The reasons for the lack of agreement in the two studies are far from obvious, and speculation can only be rough. Certainly the difference in how the atmosphere ocean interaction is modeled may play a role (i.e., the NCAR model uses fixed sea surface temperatures, whereas the GISS model computes sea surface temperatures from a simple ocean mixed-layer model). In fact, the number of differences in the two studies largely precludes any straightforward analysis of discrepancies.

Daily Variability

Daily variability of temperature can be compared for two season months (January and July) at the four locations using the standard deviations (Table 17-4). Each study also examines changed daily variability using some other statistical measure (chi-squared test of distribution similarities in the GISS study and innovation variance comparison in the NCAR study), but these are not comparable. Comparisons on the basis of standard deviations alone cannot be statistically tested because of problems encountered in meeting the assumptions required for the tests, (although in a later version Rind et al. does apply tests to the standard deviation after correcting for dependence in the sample size). Hence, these comparisons must be viewed strictly qualitatively.

In seven of the eight cases, the studies agree (that the model overestimates daily temperature variability). In the case where there is disagreement (Great Plains, July), the NCAR difference is not statistically significant on the basis of tests on the innovation variance (the variance after the effect of autocorrelation is removed). However, the GISS discrepancy is fairly large, suggesting that there is an overestimation by the GISS model. Still, the overall agreement is that the models tend to overestimate daily variability at these four locations. This tendency is graphically illustrated in Figures 17-6a and 17-6b, where the observed and model histograms of daily temperature for April at the Great Lakes (GL) grid for the two studies are compared.

In both studies, explanations for the overestimations are related to the modeling of surface hydrology, i.e., that both models fail to completely account for important surface-atmosphere interactions that would tend to reduce daily temperature variability.

Table 17-4. Daily Temperature Standard Deviations (°C)
(Rind et al. and Mearns et al.)

	GISS		NCAR	
	Obs.	Model	Obs.	Model
January				
Great Plains	4.81	8.15	4.81	8.15
Southeast	4.53	6.90	5.41	5.92
Great Lakes	4.97	5.79	5.5	11.20
West Coast	3.63	5.86	4.1	5.0
July				
Great Plains	1.74	2.56	2.90	2.79
Southeast	1.50	2.34	1.55	1.70
Great Lakes	2.38	3.02	2.67	2.82
West Coast	2.40	3.56	2.18	3.52

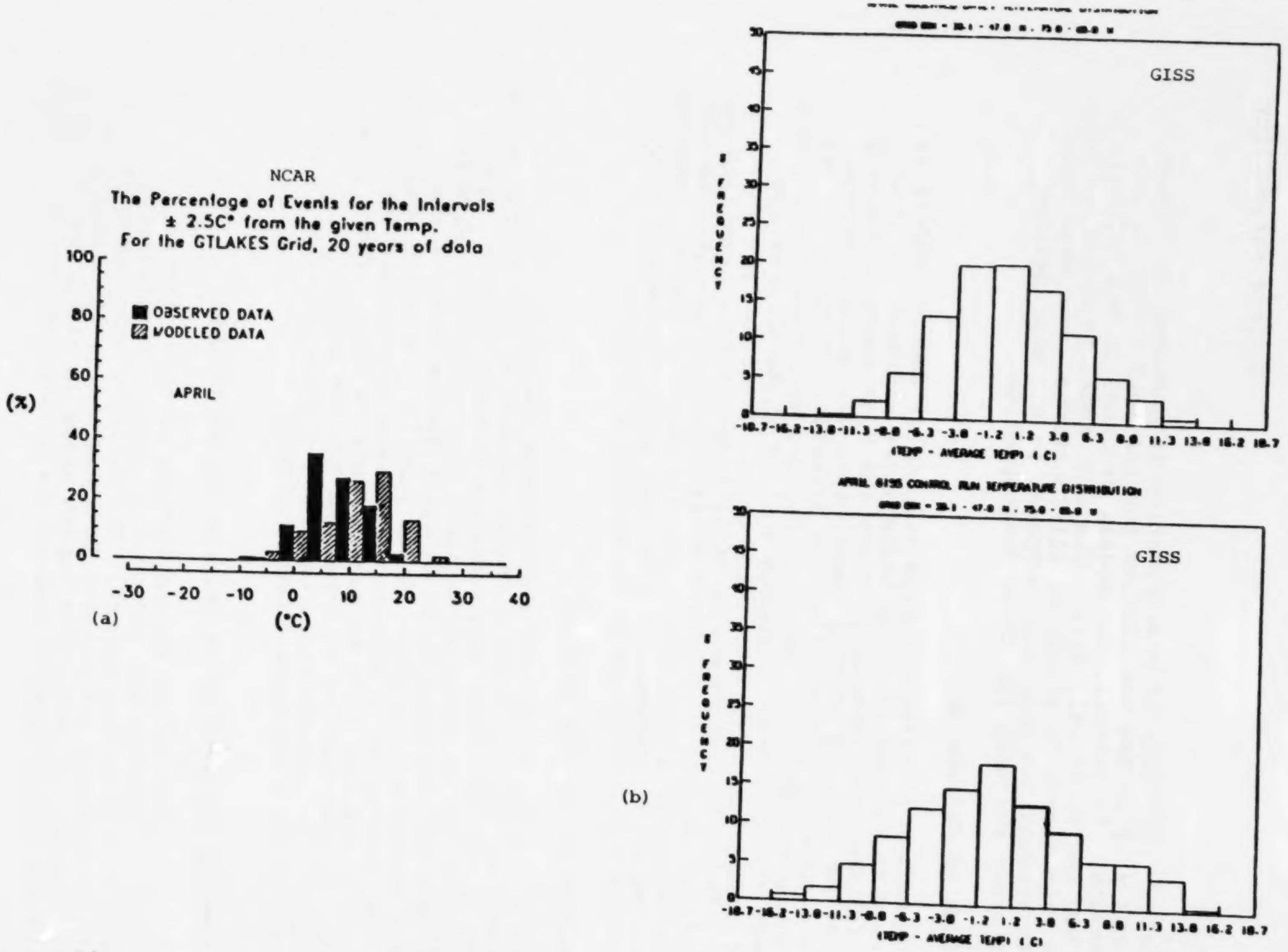

Figure 17-6. The percentage of events for the intervals ± 2.5°C from the given temperature.

Source: Rind et al., Volume _; Mearns et al., Volume _.

Daily variability of precipitation is compared by summary statements made in the two studies for the four locations for four seasons. In general, the models produce, in the majority of cases, too few light rain days. The GISS model produces too many extreme rain events in winter at all locations. The NCAR model tends to produce too many high extremes in all four seasons. Neither study accounts for these discrepancies.

Comparison of Climate Change

Comparison of climate change results of the two models is restricted to changes in daily temperature variance for four months for the four locations, since the NCAR study includes a quantitative analysis of only temperature variability change. The two studies do not agree on the direction of change of daily temperature variability. The NCAR results are mixed showing both increases and decreases, although most of these changes are statistically insignificant. Rind et al. conclude that in general, there is a decrease in daily temperature variability on the basis of changes in standard deviations (but the changes are not statistically significant). On the basis of the two research reports, no clear statement may be made about changes in daily temperature variability under CO_2 warming conditions.

Limitations of the Two Studies

It should be noted that both studies underline the importance of viewing climate change results of the models in the context of how well they reproduce the present climate. Model deficiencies can be expected to limit the reliability climate change results, and that faith in quantitative results are probably misplaced. However, model results give crude estimates as to the importance of physical processes responsible for variability and what must be done to improve them. There is a need for further testing to determine how the models' deficiencies in reproducing present-day climate affects predictions for a CO_2-warmed future climate.

IMPLICATIONS FOR STUDIES OF CLIMATE CHANGE IMPACTS

As indicated in the second section of this chapter, virtually all systems are affected by climate variability, although some more than others. The relative importance of climate variability and changes in variability, as a result of climate change, to particular impact areas is reflected in the results and limitations of some of the studies summarized in this report.

Of greatest concern was the lack of information regarding changes in the variability of temperature and precipitation that would attend climate change. The lack of this information resulted in the formation of climate scenarios wherein the temporal variability of both precipitation and temperature were not changed (see Chapter 3 on scenario development). This was considered a limitation or concern in many studies, some of which are discussed below.

In the Johnson et al. study on agricultural runoff and leaching (reviewed in Chapter 10, Agriculture), the results were considered to be limited by the failure to consider changes in storm frequency and duration that would result from climate change. Such changes would obviously affect the results of the Pesticide Root Zone Model (PRZM), which determines the distribution and transport of pesticides in soils. Also, the frequency of precipitation was left unchanged from the present-day climate and, hence, estimates of total annual erosion could be underestimated. Furthermore, the magnitude of extreme rainfall events could be exaggerated, since the number of days of rainfall is not changed, but different (usually larger) amounts of rainfall are assumed. This could result in overestimation of pesticide losses through soil erosion and leaching in a particular year. The results of this study could be vastly different from those presented, depending upon assumptions concerning precipitation duration, frequency, and intensity, all of which would change if a changed daily variability were assumed.

Several studies on hydrology summarized in this report also are highly dependent upon assumptions about precipitation variability. These include the Lettenmaier et al. study on the hydrology of catchments in the Central Valley and the Sheer and Randall study on the impact of climate scenarios on water deliveries, both reviewed in Chapter 6. The hydrologic inputs for the models used in these studies are interdependent. Lettenmaier et al. assumed that the number of days of rainfall remains the same under the climate change. Model results in terms of predicting runoff amounts would be quite different if more rainfall events of lower intensity were assumed compared to the same number of rainfall events with (generally) higher intensity. Since the Sheer and Randall study uses the output of the Lettenmaier study as hydrologic inputs to their water delivery model, their results are also dependent upon the assumptions about unchanged variability and, hence, their results could also change considerably if precipitation variability changes were considered.

The studies for the Southeast (Chapter 6) did not consider changes in the frequency of droughts or severe storms such as hurricanes, which could certainly affect the likelihood of flooding for some coastal communities. However, these concerns are considered secondary to changes in sea level that would dominate in terms of changing the likelihood of floods.

Crop yields are very dependent on daily variability. For example, heat waves during grain filling lower wheat yields. Whether a drought occurs early or late in the growing season has differential effects on yields. Changes in variability were not considered in the Rosenzweig, Peart et al., Ritchie, and Dudek studies.

Changes in the frequencies of extreme events are considered to be of great importance to potential forest disturbance, as discussed in Chapter 11. Here, an important distinction is made between the ability of forests to adapt to changes in mean climate conditions versus changes in extremes. The possibility of increases in the frequencies of events such as wind, ice, or snow storms, and droughts and flooding may be of greater significance to forest survival than the gradual mean change in climate that has been studied so far.

The Kalkstein study, which is reviewed in Chapter 14 on Human Health effects, is strongly dependent upon the determination of certain maximum temperature threshold values beyond which human mortality increases. In applying the death/weather effects statistical models to scenarios of climate change, temperature variability is held constant, so that temperatures that exceed the threshold values are determined unrealistically. Of course, there is greater accumulation beyond the thresholds in the warmer scenarios, but not to the same extent as would be the case if the both variance and mean of the series are changed. This problem is explicitly stated in the section on limitations.

Changes in the variability of temperature both seasonally and daily are important to studies concerned with the effect of temperature change on the change in electricity demand discussed in Chapter 16. Although new generating capacity requirements for the nation for 2010 and beyond are calculated assuming climate change, the numbers generated could be considerably different for any particular year depending mainly on air-conditioning needs, which would be the major use increase for electricity. Such needs are sensitive to extremes in daily maximum temperatures and the persistence of such temperatures (i.e., heat waves).

Potential change in extreme events is identified as a research need in this chapter.

It would be impossible to quantitatively or even qualitatively estimate how different the results of these studies would be if changes in climate variability had formed part of the climate scenarios made available as input for the various climate impact models used. Primarily, it is impossible because the variability changes are not known; second, it is impossible because most of the studies are of such complexity that the effect of a change in one variable (a complex change at that) is not intuitively obvious in most cases. Sensitivity analyses of the impact models involved to changes in variability would be required to provide specific answers. What can be said at this point is that the lack of information on climate variability has limited a number of studies in this report and has limited the completeness of the answers they could provide. The magnitude of change of some impacts could be affected by the inclusion or exclusion of variability information.

FUTURE RESEARCH NEEDS

The research reported above clearly indicates that research of changes in climate variability with climate change is truly in its infancy. Much needs to be done. Future research needs may be broken into three categories.

1. Further investigation of variability in presently existing GCM control and perturbed runs. Results summarized here represent only an initial effort at looking at variability in GCMs. The first research priority is to examine at many more grid boxes the daily and interannual variability of many climate variables in addition to temperature and precipitation, such as relative humidity, solar radiation, and severe storm frequency. Moreover, the most sophisticated statistical techniques must be used or where needed, developed, such that uniform quantitative indicators are available to evaluate both how well the current models reproduce present variability and how they forecast the change in variability under climate conditions. The causes for discrepancies in present-day climate variability and control run variability must be better understood, so that a clearer understanding of future climate changes can be attained.

2. Improvements in GCMs geared toward better reproduction of climate variability. From the results of Rind et al. and Mearns et al., some indications are given that oversimplifications in the land surface packages of GCMs contribute to overpredictions of daily temperature variability. This possibility is further underlined by the better results obtained with Dickinson's model, which includes a more sophisticated land surface package. More detailed analyses of current GCMs are necessary to confirm this speculation as well as to determine the causes of other errors in variability such as for precipitation. The next step involves altering the GCMs so that variability is properly simulated. Only then can much faith be put in GCM forecasts of variability changes with a perturbed climate.

3. Sensitivity analyses of climiate change impact models to changes in climate variability. It also must be determined how important changes in variability will be to different areas of impact. Since the variability of climate variables produced from GCMs cannot be "trusted" or even easily analyzed at this point, these sensitivity analyses of impact models should be performed with statistically simulated time series of climate variables, as has been performed by Schwarz (1976) and Mearns et al. (1984). By simulating time series, different levels of autocorrelation and variance in the time series may be controlled for and systematically varied. By this means, important thresholds of variability change for different variables as they affect the output of impact models can be determined. Moreover, ranges of possible impacts of variability change can be determined and can serve as guides until better information is available on how variability will change in a CO_2-warmed world.

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DRAFT

CHAPTER 18

RESEARCH NEEDS

The Environmental Effects report has summarized the results of over 50 individual research projects interpreted from regional and national viewpoints. As described in previous chapters, this report is organized around a series of regional case studies performed for the Great Plains, the Southeast, the Great Lakes region, and north-central California, as described in Chapter 1. In addition, several larger environmental issues, such as impacts on agriculture, forest resources, coastal zones, and water demand, were analyzed from a national perspective. In each regional and national study, an attempt was made to make use of the highest quality and most recent science available. This process has resulted in two outcomes:

1. The results provide insight about the sensitivities of different sectors and regions to climate change.

2. The results themselves raise new scientific questions and issues that cannot now be resolved. For example, the importance of certain climate data for impact analyses has been recognized. The following partial list of examples may be helpful to circulation modelers:

   - the importance of winds in analyses of Great Lakes levels;

   - the need for information on major storms and hurricanes to fully assess impacts on coastal regions;

   - the role of water vapor, clouds, boundary layer, and windspeed and direction for air quality analyses;

   - the impact of precipitation variability on pesticide runoff studies;

   - the effect of changes in freezing conditions on ice cover in the Great Lakes and on snow pack in California;

   - the importance of soil moisture and temperature on forest growth;

   - the effect of temperature and precipitation variability on agriculture;

- the role of water runoff for future estimates of hydroelectric power, flood control, and water quality; and
- the possible importance of synoptic weather patterns on health.

This chapter summarizes the major scientific research issues on the environmental effects of climate change that the Environmental Protection Agency has identified while preparing this report. It is not our purpose to make recommendations to the U.S. Government or to the full scientific research community. However, we have, where appropriate, suggested areas where strong research coordination should occur and have attempted to describe where such research coordination is already occurring.

Detailed research needs have been identified and justified in each chapter. Table 18-1 summarizes these research needs for several major topics. The assumption that underlies both this table and the overall research strategy is that focusing on regional-scale effects from global atmospheric change is an effective way to address scientific issues relevant to environmental policymakers. This report has upheld that initial assumption, and we expect that future research on impacts in other parts of the globe and on other resources will do so as well. In addition, however, it will be important to understand broad national consequences of the regional impacts of climate change. We propose that this can be accomplished by giving careful attention to both aspects in research, and by conducting scientific studies and policy studies in close cooperation, as has been done in this report.

This chapter contains four main sections:

1. A description of the research role that EPA will play in the U.S. Government's overall research program in global climate change;
2. A description of the main research thrusts to be pursued in the environmental consequences of global climate change;
3. A description of the supporting atmospheric science research that will be necessary from the standpoint of understanding environmental effects; and

4. A short summary of the research topics implicit in integrating regional and national-scale research issues in such a way that they are relevant to the development of environmental policy.

THE ENVIRONMENTAL PROTECTION AGENCY'S RESEARCH ROLE

EPA's main responsibility is to develop, implement, and enforce policies to protect human health and the environment. In recent years, the concept of risk assessment and risk-based decisionmaking has been used as a model for developing policy-relevant scientific information in a logical fashion that takes into account the inherent uncertainties in data and understanding (Ballou et al., 1981; Barnthouse et al., 1982; Harwell and Harwell, 1988). While this concept has its roots in health and toxicological research and regulatory activities in EPA (North and Yosie, 1987), it can also be extended in concept to other, more ecological issues.

Global climate change presents a challenge to this concept, as EPA, other Federal agencies, and international research organizations have discovered. Since probable losses due to climate change cannot be quantified in a truly predictive fashion, a strong research emphasis must be placed on scientific assessment: we must identify not only what we do and do not know, but how well we understand the possible consequences of change. The role of EPA's research program and other research programs should thus clearly be to provide understanding and scientific assessments necessary to develop policy options and to analyze their consequences for the environment.

EPA and the U.S. Government are moving strongly in this direction. The Global Climate Protection Act of 1987 directs EPA and the State Department to coordinate the development of national policy for global climate change. This coordination involves many other agencies with essential policy roles, such as the Department of Energy. In addition, the act directs EPA, in cooperation with other agencies, to prepare a scientific assessment of climate change with international scope and representation. EPA has been designing the scientific assessment in cooperation with several Federal departments and research agencies: the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the National Science Foundation, the U.S. Geological Survey, the Department of Energy, the Office of Naval Research, and the U.S. Department of Agriculture. These agencies, along with the State Department, have been organized under the auspices of the Committee on Earth

Sciences in the Office of Science and Technology Policy and in cooperation with the National Climate Program Office. The scientific assessment will address the scientific information that is important for policymakers to consider as they move toward developing policy options.

Within the U.S. Government, EPA's overall role encompasses both policy development and scientific research. In scientific research, its main responsibility will be to understand the potential consequences of global atmospheric change, the anthropogenic contribution of global change and options to minimize it, and the development of adaptation responses.

That responsibility and the research in this report have led to the formulation of several important scientific questions that are also relevant to EPA's policy mission. These questions should be thought of as overriding themes, rather than as a list of all the potential issues:

- What is the likelihood of a change in the global climate system, occurring over the next several decades to a century, that is clearly attributable to anthropogenic influences?
- How will climate and atmospheric chemistry change in different regions?
- What is the extent and magnitude of ecological and environmental change associated with changes in regional chemistry and climates?
- Over what time spans are regional atmospheric change and subsequent ecological changes likely to occur?
- What are the potential impacts of climate change on environmental resources?

These policy-oriented questions are viewed as the beginning stages for analyzing possible environmental changes resulting from climate change and eventually analyzing the possible avenues of managing risks. They also define the specific areas in which EPA will conduct and sponsor research, e.g., emissions of trace gases, global atmospheric chemical modeling, regional atmospheric consequences of change, regional environmental consequences of change, and monitoring of sensitive ecosystems for change.

Goals and Objectives

The major research goals and objectives of EPA's research program have been structured to address the policy-oriented questions. They reflect the need to establish scientific direction that is consistent with major policy uncertainties. In so doing, the goals and objectives are more technical statements of research needed to address the policy questions.

The goals of EPA's proposed research are the following:

- To assess the probability and magnitude of changes in the composition of the global atmosphere, and the anthropogenic contributions to those changes, for the purpose of evaluating the likelihood and magnitude of subsequent climate change.
- To assess the likely extent, magnitude, and rate of regional environmental changes as a function of variability in climate, for the purpose of evaluating the risks associated with changes in the climate system.

Since this report has focused on the effects of climate change, and not on the processes leading to climate change, we will focus here on the second goal. The following objectives relate to this goal:

- To relate global scale changes in climate and chemistry to regional scale changes by constructing a series of regional atmospheric scenarios.
- To predict environmental responses to climatic variation and to test the processes that control those responses.
- To document the spatial covariation of regional climate change with regional ecological change to establish comprehensive ecological monitoring in selected locations, cooperatively with other EPA and Federal programs.
- To produce periodic scientific assessments in conjunction with other Federal agencies and international research organizations, and to perform research to evaluate the consequences of adaptation policies.

ENVIRONMENTAL CONSEQUENCES OF CLIMATE CHANGE

Background

The long-term goal of the environmental research proposed is to create quantitative regional models of environmental responses to climate change for decisionmakers. These models need to explain landscape-level and multi-resource interactions, e.g., links between air quality, forest health, and climate change, that are beyond the scope of this report. Before such models can be created, however, many gaps in knowledge remain to be addressed.

Research still needs to be done that will (1) identify regions and resources sensitive to global climate change; (2) establish quantitative, causal relationships between climate and selected ecological indicators and attributes of concern; (3) predict the impact of changing climate on selected systems and regions; (4) refine the assessments and methodologies to include quantitative, multi-resource interactions; and (5) develop the ability to address multiple stressors, integrated at the regional scale.

The process consists of four generic steps:

- Classify and characterize the environmental resources of concern;
- Determine the resources' current status, recent trends in condition, and possible associations with climatic variability;
- Use mathematical models to estimate future status under different climatic scenarios; and
- Characterize the possible changes in each system by sensitivity studies, and by formally considering the uncertainty inherent in the mathematical models and underlying data.

Objectives

In the first phase of research, one must continue to identify resources and regions sensitive to climate change through review and synthesis studies (e.g., NAS, 1982; MacCracken and Luther, 1985; Trabalka, 1985; Bolin et al. 1986; Shands and Hoffman, 1987; White, 1985). These studies will proceed from the identification of extant data through exploratory analyses and model enhancement to regional characterizations of environmental changes associated with global climate change. The second phase will build on the first to initiate experimental studies investigating causal relations among climatic stressors and ecological responses at the ecosystem, landscape, and regional scales. In the third phase, several years away, research should emphasize trends detection, long-term experimental manipulation, and model testing and refinement. In each phase, close cooperation with the U.S. land management and research agencies will be necessary for success.

The following objectives are identified for each of the above phases.

Short-Term Objectives

- Define environmental sensitivity qualitatively, and identify sensitive climatic, biotic, and aquatic regions for study using extant data.
- Produce conceptual models of expected climate-induced responses, including changes in biogenic sources of radiatively important trace gases.
- Prioritize the regions and systems, as well as the most appropriate temporal and spatial scales, for in-depth observational and experimental (field and laboratory) studies.

Mid-Term Objectives

- Establish quantitative, causal relationships between climate and selected environmental attributes of concern, and begin to quantify the uncertainties.
- Proceed from qualitative to quantitative, predictive models.
- Produce preliminary predictions of changing climatic impacts on selected systems and regions, and quantify the uncertainties.

Long-Term Objectives

- Refine the assessments and methods produced in the first two phases to include quantitative, multi-resource interactions.

- Develop and validate capabilities to address multiple stressors and resources, integrated at regional scales for decisionmaking.

Research Strategy

This report has clearly shown that concerns over the adaptability and fate of natural ecosystems are well founded. Forested ecosystems, aquatic and marine biota, wildlife in refuges, water quality in small lakes, and certainly other resources may be unresistant to rapid climate change. The strategies for mitigating changes in these systems are likely to be large and exceedingly difficult to implement. Consequences for environmental attributes such as biodiversity, primary productivity, and cycling of nutrients, while difficult to quantify, may be equally difficult, if not impossible, to reverse. Federal agencies with both stewardship and research responsibilities for managing natural resources such as the U.S. Forest Service, the National Park Service, the Fish and Wildlife Service, the U.S. Geological Survey, the Bureau of Land Management, and the National Oceanic and Atmospheric Administration, should recognize that data, models, and continued research on these environmental resources and attributes are vital. This report has additionally shown that while intensively managed ecosystems, especially agroecosystems, may also be affected by a climate change, there seem to be more opportunities for human intervention to mitigate or adapt to the response. Thus, the critically important questions become whether or not the capacity for human intervention can keep pace with the rate of change induced by changing climate. Areas of major interest, therefore, are historical changes in the distribution and yield of agroecosystems as a function of climate, interactive effects of climate change and carbon dioxide increases on crop yields, and the adaptation rate of management practices. The Agricultural Research Service and Department of Energy have been, and should continue to be, important contributors to these research areas. Whether the same generalizations will hold for agriculture abroad remains to be investigated, and EPA will cooperate with U.S. and international organizations to explore this issue further.

Other managed environmental resources, such as air and water quality, or the preservation of coastal wetlands, are already subject to regulation, but may well be sensitive to climate change, as shown in Chapters 8, 9, and 13. EPA will investigate the possible consequences of climate change for these resources, examine their influence on ecosystems, and analyze the implications for regulatory policies. Other already regulated resources, such as drinking water and groundwater, may also be investigated.

Possible impacts on human health, as emphasized in this report, are both troubling and very difficult to quantify. The correlative studies reported in Chapter 14 need to be substantiated with more targeted research on the mechanisms of impact. While EPA is not likely to be a major contributor in this area, other organizations, such as the National Institutes of Health or the National Institute for Environmental Health Studies, may be logical sponsors for further research. The possibilities that disease vectors may change their distributions as a function of climate change, while speculative, should be pursued more completely. To the extent that these are as much ecological questions as they are health questions, contributors will include EPA as well as organizations such as the Centers for Disease Control.

It is clearly not possible to study all potential effects. Because of the concerns raised in this report, and EPA's responsibilities for understanding the consequences of climate change, initial focus will be on the possibilities of irreversible change as well as when changes may occur rapidly. Therefore, early work will concentrate on providing data on the sensitivities of environmental systems to climate change, constructing conceptual models, and providing input to future regional and national-scale assessments. Later research will lead to increasingly quantified understanding of environmental response to climate change in several research areas: regional environmental attributes, feedbacks, scaling issues, disturbance regimes, and landscape interactions.

To conceptually organize research, attributes of systems will be investigated as a function of ecological and biotic regions (Solomon and West, 1985; Braun, 1950; Brown and Lowe, 1980; Fowells, 1965; Vankat, 1979; Wells, 1979). Then the structural and functional aspects of each attribute will be investigated. Ecosystems and regions will be defined by extant environmental conditions and existing data, with boundaries along maximum rates of change in system attributes. Ecosystems and regions will therefore be well defined near the center of their range or distribution. The boundaries will necessarily be less well defined, but they will be more precisely delineated as a function of continuing analyses. Examples of similar approaches to resource definition are shown in Figures 18-1 through 18-3.

The different scales of spatial patterns on the ground can impart great difficulties in the "scaling up" of local processes. Therefore, a high priority is to develop the ability to interpolate from large spatial scales to small and extrapolate from local patterns and processes to regional generalizations.

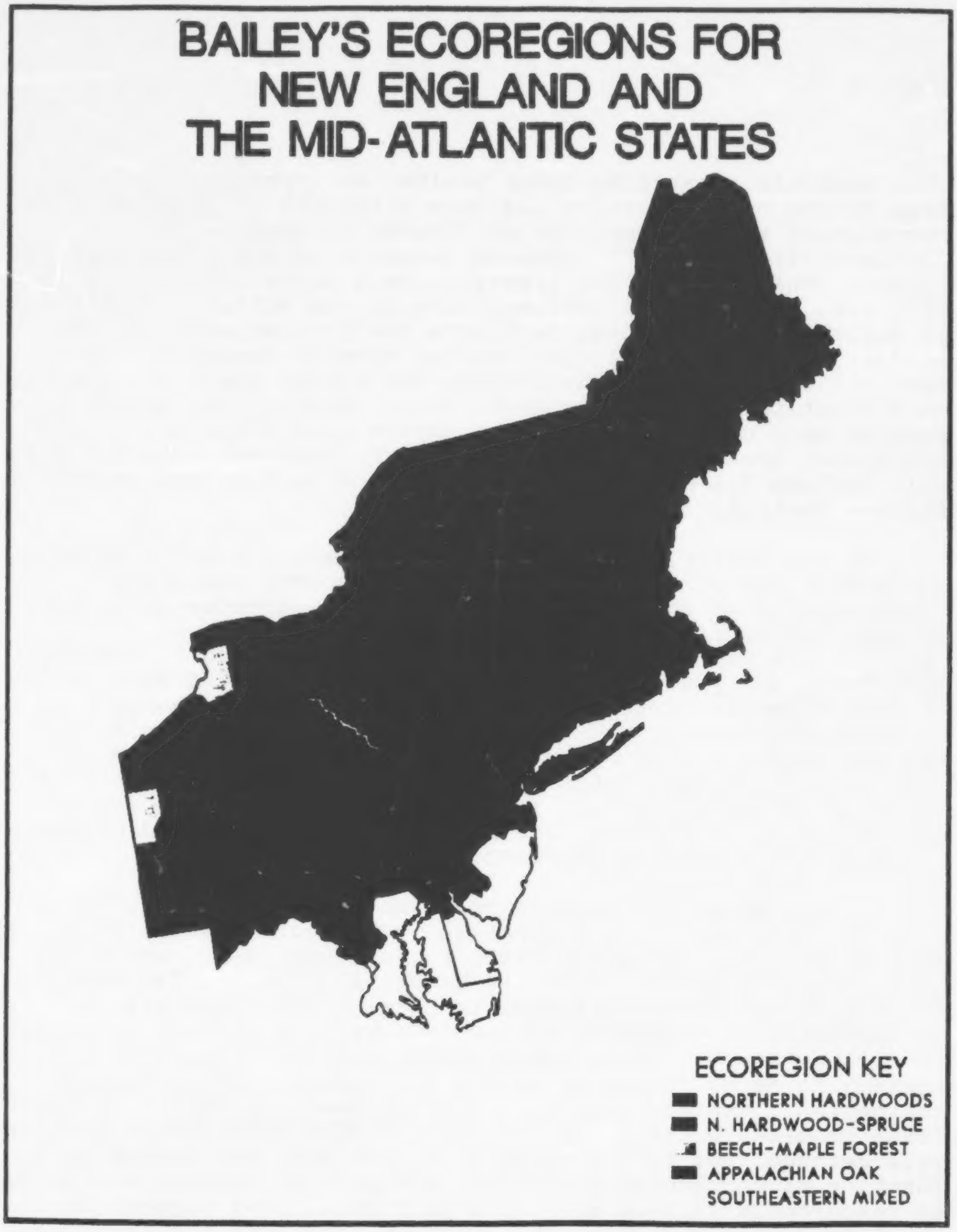
BAILEY'S ECOREGIONS FOR NEW ENGLAND AND THE MID-ATLANTIC STATES
ECOREGION KEY
■ NORTHERN HARDWOODS
■ N. HARDWOOD-SPRUCE
■ BEECH-MAPLE FOREST
■ APPALACHIAN OAK
SOUTHEASTERN MIXED

Figure 18-1. Bailey's ecoregions for New England and the Mid-Atlantic States.

Source:

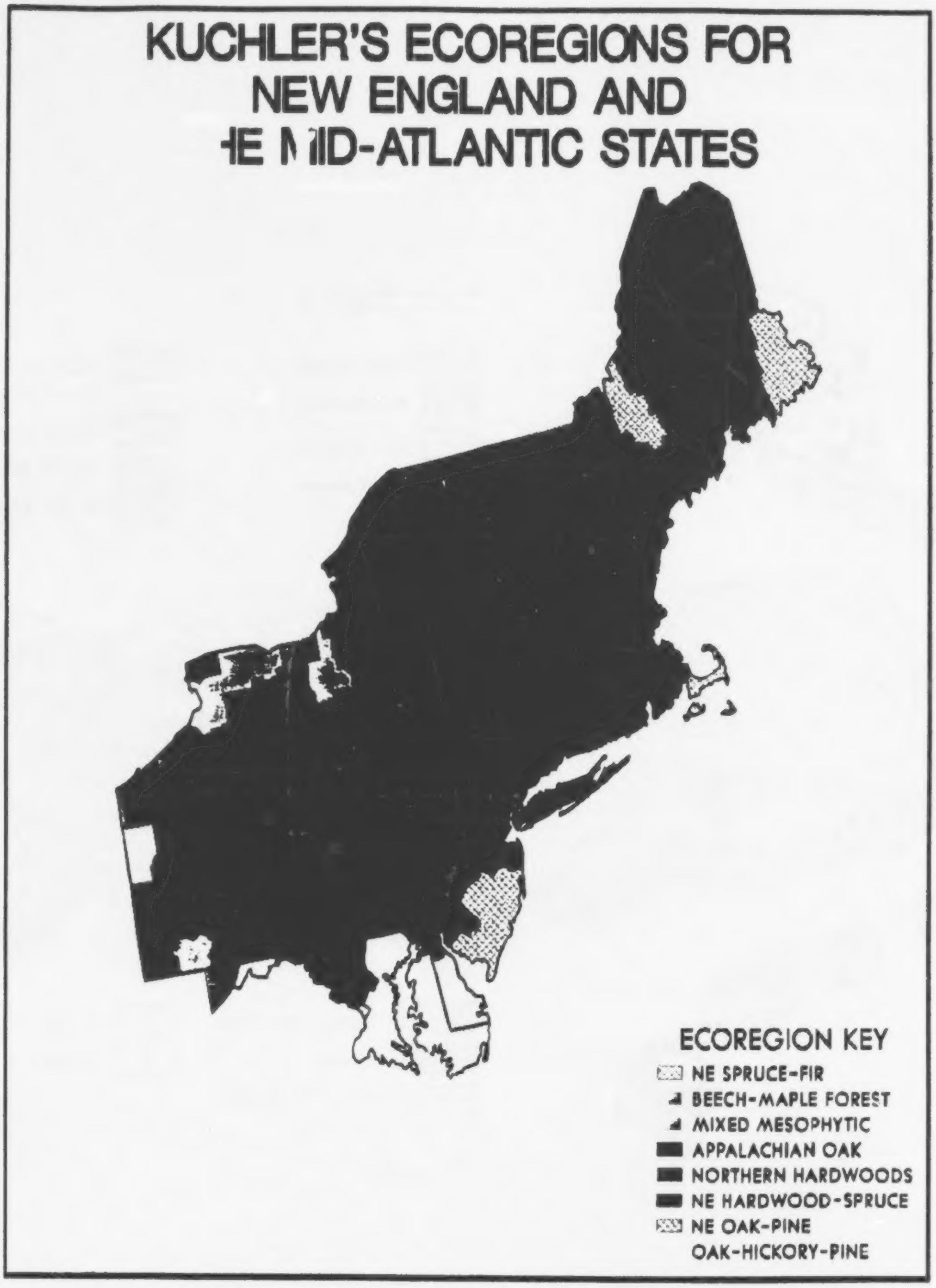
KUCHLER'S ECOREGIONS FOR
NEW ENGLAND AND
HE MID-ATLANTIC STATES
ECOREGION KEY
▨ NE SPRUCE-FIR
◢ BEECH-MAPLE FOREST
◢ MIXED MESOPHYTIC
■ APPALACHIAN OAK
■ NORTHERN HARDWOODS
■ NE HARDWOOD-SPRUCE
▨ NE OAK-PINE
OAK-HICKORY-PINE

Figure 18-2. Kuchler's ecoregions for New England and the Mid-Atlantic States.

Source:

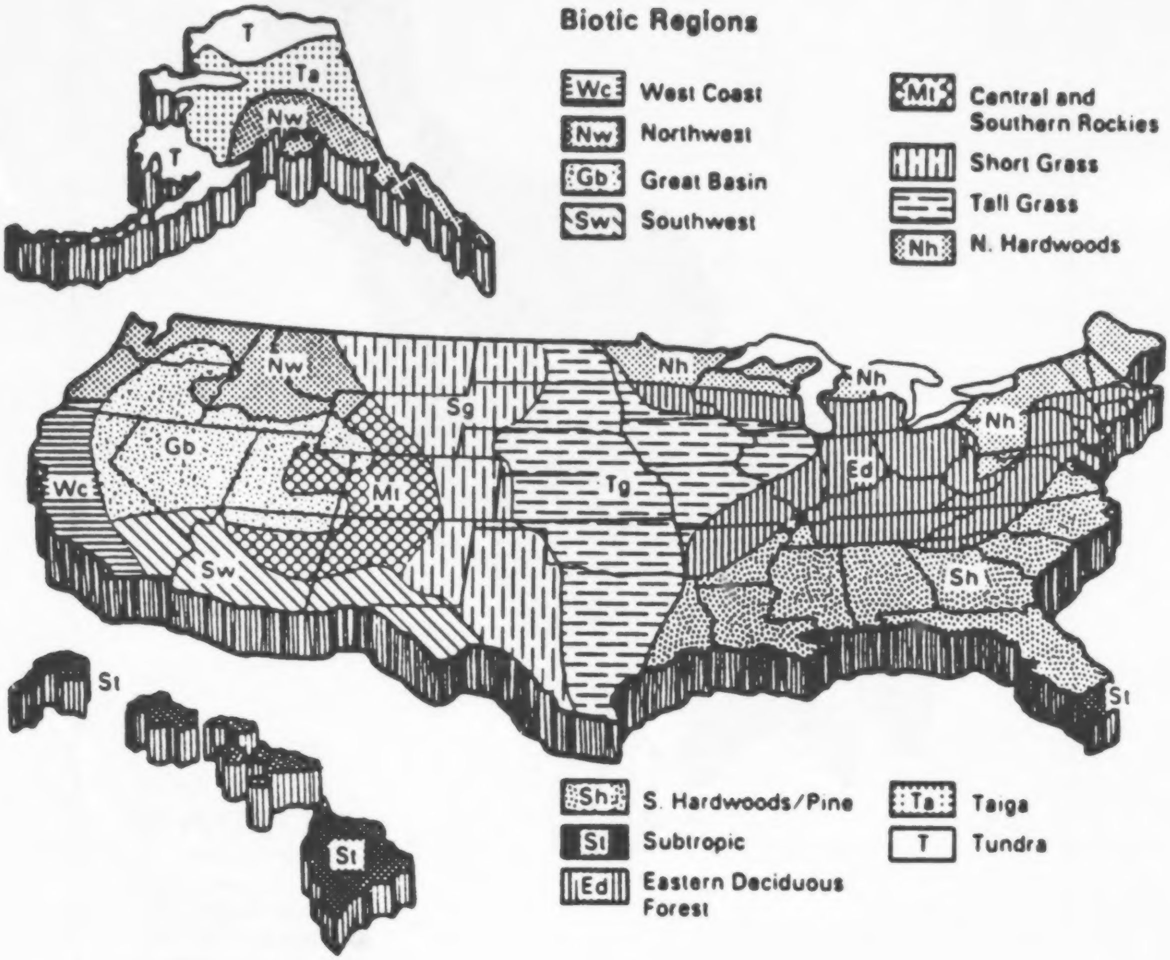
Biotic Regions
Wc West Coast
Nw Northwest
Gb Great Basin
Sw Southwest
Mt Central and Southern Rockies
Sg Short Grass
Tg Tall Grass
Nh N. Hardwoods
Sh S. Hardwoods/Pine
St Subtropic
Ed Eastern Deciduous Forest
Ta Taiga
T Tundra

Figure 18-3. Major biotic regions of the United States.

Source: Compiled from Braun (1950); Fowells (1965); Vankat (1979); Wells (1979); Brown and Loew (1980).

Intercalibration of measurement approaches will improve confidence in results and should allow low-cost regional estimates from satellite measurements. The National Science Foundation, the National Aeronautics and Space Administration, and the National Oceanic and Atmospheric Administration will be key contributors to this research. However, a significant investment in methods development of sensors as well as ground-truthing must be done before this goal becomes a reality. Analysis of the effects of changes in climatic variability is critical to understanding potential environmental changes. Variations in the frequency of weather events are important for many environmental processes, and the rates of those processes may vary as a function of both spatial scales and temporal scales. Changes in climatic variability will be critical as the problem to be addressed becomes one of attempting to predict the occurrence of large-scale, rapid changes in the biosphere.

Critical feedbacks in ecosystem distributions result from (1) interactions between bordering systems, such as the forest-prairie ecotone; (2) differential lags, such as the different migratory and developmental rates of different kinds of organisms and physical components within any given system; (3) interactions between biogeochemical processes and population processes; and (4) boundary layer effects.

The differing lifespans and dynamic processes in the soil-plant-atmosphere continuum create lags that will cause the response time of systems to differ substantially from the rate of climate change. Changes in the biogeography or distribution of species will change biogeochemical balances, which will then change the size of reservoirs of carbon and other elements, thus changing the rates of production of some radiatively important trace gases.

Physical and biological disturbances on any scale exercise considerable influence over the patterns and processes of ecological systems on both larger and smaller scales. Frequency, extent, and magnitude of disturbances will likely change as a function of global climate changes. The relationships between disturbances and ecological responses will therefore be critical to any modeling that attempts to predict the appearance and rate of change of large areas of landscape.

The initial stages of research should involve the following: (1) setting priorities for systems and regions, based on initial concepts of sensitivity and results from studies in this report and others; (2) constructing conceptual models; and (3) providing preliminary information for national-scale assessments of environmental effects of climate change. The major indicators of regional sensitivity to be used should include natural variability of weather and concomitant variability in the growth and distribution of major plant species, based on historical records and proxy data.

Early scientific assessments should provide information on (1) location of sensitive regions, and (2) conceptual models that include causal processes. To evaluate the potential sensitivity of regions, landscapes, and ecosystems, the temporal variability in the spatial distribution of both weather patterns and ecological resources must be analyzed systematically. This is difficult, because increased resolution on one scale generally results in decreased resolution on the other. However, the results will provide the conceptual models of regional responses to global climate change. A similar approach is applicable to aquatic biota and water resources, wetlands, agriculture, and other environmental resources.

The general procedure is to identify climatic regions, as determined by both temporal (seasonal) and spatial variability in weather patterns (Borchert, 1959; Bryson, 1966; Mitchell, 1969; Wendland and Bryson, 1981). Climatic regions so identified are then associated with attributes of corresponding environmental and ecological systems that might be sensitive to these changing weather patterns. The zones of seasonal weather patterns and interannual variability can then be analyzed for covariation with corresponding data on major natural resources, such as vegetation distribution and growth (Braun, 1950; Fowells, 1965; Vankat, 1979; Wells, 1979; Brown and Lowe, 1980). Characteristics of the plant distributions, specifically species boundaries or transition zones, are related through causal hypotheses to variability in weather patterns. These characteristics and model results are then used to indicate the expected future covariation between climatic and natural resources regions, ecotonal areas, and ecosystems potentially sensitive to large-scale shifts in the climate system.

The critical areas to be identified during these analyses include (1) links between indicators of climate change and upper atmospheric weather patterns; and (2) links between upper atmospheric weather patterns, surface weather patterns, and resource variability (Neilson, 1986); thus providing (3) links between indicators of climate change and resource variability. This information can then be integrated to evaluate the expected responses in resource indicators to a change in the climate system. The entire process yields mechanistic, conceptual models of regional ecosystem responses to global climate change.

This approach can also be used to identify potentially susceptible water resources and surface water regions of the country (Figure 18-4) (USGS, 1986). This will produce a depiction of the processes that control seasonal runoff patterns and their year-to-year variability, as well as a direct relationship between rainfall and runoff at a regional scale. The interactions between regional rainfall, runoff, vegetation cover, soil moisture, and evapotranspiration will then need to be addressed. Integrating hydrologic flows, land-use patterns, and ecosystem dynamics will allow characterization of water quality patterns within regions. These associations can then be used to characterize the effects of climate change on water resources on regional spatial scales.

The biotic and hydrologic studies then must be integrated to identify regions and sites for future experimental study. This is critical as terrestrial, aquatic, wetland, and coastal systems do not exist in isolation; their interactions affect each ecosystem both directly and indirectly.

Experimentation, Modeling, and Monitoring

Field and laboratory experiments will be required to address directly some of the proposed mechanisms and ecological processes that mediate landscape and regional scale responses. Experimentation will assist in model development, model calibration, and identification of baselines against which change can be measured.

Experiments and observations should assess quantitatively the changes in resources as a function of position along regional environmental gradients. Attributes to be assessed include (1) past variability of resources to climate change; (2) establishment and mortality of plant species; (3) decomposition and productivity patterns; (4) successional and biodiversity patterns; (5) biogenic emissions of trace gases; and (6) runoff and water quality patterns.

Monitoring studies must be initiated for the purposes of (1) resolution of ecological patterns at different temporal and spatial scales; (2) regional detection of trends; and (3) calibration and validation of models. The locales, systems, and attributes to monitor should be based on the extant data analyses and field studies outlined above.

Modeling experiments should be performed to reduce uncertainties in our capabilities to predict ecological responses. Sources of uncertainties include (1) dispersal

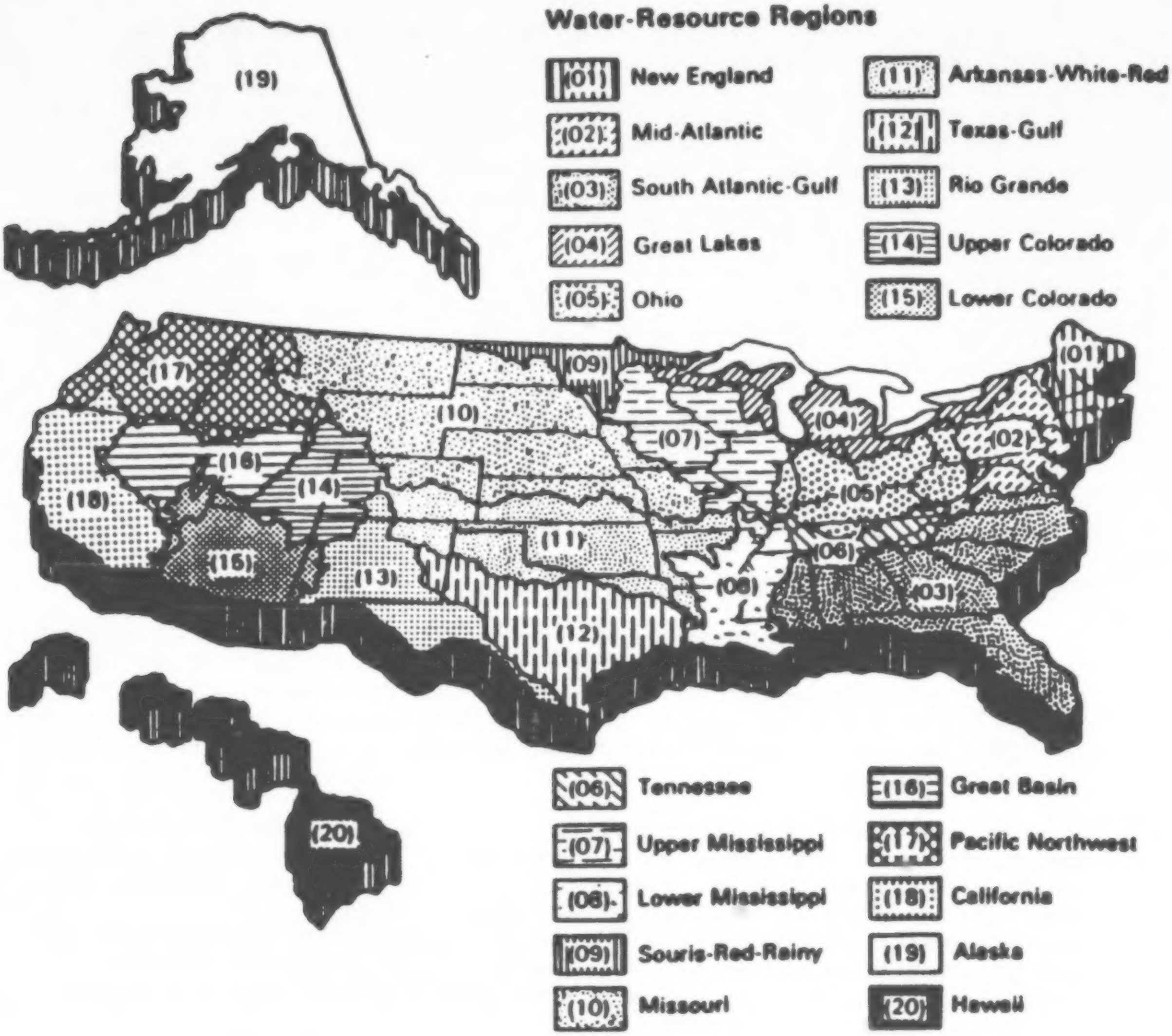
Water-Resource Regions
(01) New England
(02) Mid-Atlantic
(03) South Atlantic-Gulf
(04) Great Lakes
(05) Ohio
(11) Arkansas-White-Red
(12) Texas-Gulf
(13) Rio Grande
(14) Upper Colorado
(15) Lower Colorado
(06) Tennessee
(07) Upper Mississippi
(08) Lower Mississippi
(09) Souris-Red-Rainy
(10) Missouri
(16) Great Basin
(17) Pacific Northwest
(18) California
(19) Alaska
(20) Hawaii
(19)
(17)
(16)
(18)
(14)
(15)
(13)
(10)
(09)
(11)
(12)
(07)
(08)
(04)
(05)
(06)
(03)
(02)
(01)
(20)

Figure 18-4. Water resource management regions based on Water Resources Council and USGS delineation.

Source: USGS (1986).

through a heterogeneous and changing landscape; (2) lags imparted by life cycles of dominant organisms and ecological processes; (3) rate changes imparted by feedbacks from direct effects of CO_2 on plant processes; (4) landscape transfers of sediment, nutrients, organic matter, energy, water, and propagules among terrestrial, aquatic, wetland, and near-coastal systems; (5) geomorphic processes; and (6) possible threshold effects or synergistic effects in any of these processes, including the possibility of exotic or weedy species overrunning newly created habitats.

The modeling strategy will be most effective in a phased approach, focusing initially on developing conceptual models and critically assessing already available techniques and quantitative models. This report has begun to contribute to this phase due to its use of existing models for analysis. Components of existing models will then be evaluated for use in regional models or for direct application. Conceptual models will then provide a framework for integrated landscape and regional simulation models. Modeling exercises should initially parallel the field experiments outlined above.

Mid-term research tasks will be a direct outgrowth of earlier work and also will address major feedback loops and quantifying temporal and spatial scale relationships.

The feedback loops fall into three general categories: (1) landscape interactions; (2) direct effects of CO_2; and (3) biogenic emissions of radiatively important trace gases. Scaling issues to be resolved in this phase involve relating global scale circulation patterns to regional scale weather and then to landscape scale effects consistent with ecosystem processes.

Experimental approaches will be initiated to improve the conceptual models developed earlier and to permit more quantitative modeling and understanding. New research areas of importance include (1) remote sensing to detect areas of plant stress, to inventory possible biogenic emission sources, and to monitor ecological status; (2) ground-based inventories of possible biogenic emissions sources; (3) quantification of ecosystem-landscape processes and interactions; and (4) continued hierarchical modeling of system and landscape level responses to climate change.

This phase will make possible a more quantitative assessment of the potential ecological effects of climate change, including identification of uncertainties and directions for research to further reduce critical uncertainties. The major change is that assessments at this time will have the choice of reflecting a national scope with regional resolution or of focusing on quantitative potential effects within one or a few sensitive regions.

The next stages of model enhancement should be to formulate landscape-scale models. This will involve linking models of different resources and extending models from point or site representations to include spatial variability. Remote sensing will play a key role in calibrating and validating such models.

Simplifying modeling approaches to describe resource links will be a major challenge. One approach is "top-down" modeling, similar to the approach first used to identify sensitive regions (Landsberg, 1986). Conceptual models will be constructed from this perspective with process-based complexities added as needed. While it will be necessary to account for additional variables at individual sites, this may not be necessary for describing regional patterns.

Major emphases must be placed on linking models or model results across ecosystem boundaries. One approach will include searching for response surfaces that can directly link inputs and outputs, bypassing internal model complexities. These response surfaces could be used to represent model behavior in linked systems. The original, process-based models would be retained for testing and evaluation purposes. Linking models at both the landscape and regional scales should then provide information on the important processes and inputs at that scale, and as well as on what climatic signals are transferred to other scales.

Regional Estimates and Trends Detection

A long-term requirement for environmental effects research is an inventory of ecosystems and landscape units on a regional basis. Statistical methods for trends detection over time and space will also be needed. The land management agencies, the National Science Foundation, the Department of Energy, and EPA all have existing and planned activities in these areas. Resource inventories and ecological monitoring data must continue to be high priorities for funding, if we ever hope to be able to validate our current or planned models of ecosystem response to climate changes.

ATMOSPHERIC SCIENCES RESEARCH

The goal in the proposed strategy for atmospheric sciences research is to better understand the physical and chemical dynamics of the atmosphere to assess the impact of climate and climate change on the environment. Research is needed to produce scenarios of both physical and chemical atmospheric conditions that will support ecological assessments and policy analyses of the effect of global climate change on regional environmental resources (Kellogg and Schware, 1981; Wigley et al., 1986; NRC, 1982). We will refer to these more comprehensive scenarios simply as "climate scenarios," with reference to both the physical and chemical components of the atmosphere as climate.

Objectives

Four objectives must be achieved to accomplish the overall goal:

1. To produce regional climate scenarios that address biological and ecological responses, incorporating appropriate meteorological and chemical dynamics that are related to the expected biological effects.
2. To produce regional climatic scenarios that allow assessments of future tropospheric and boundary layer air quality for regulatory and policy analysis.
3. To enhance understanding of the atmospheric phenomena controlling impacts by producing models that describe the physical and chemical processes and their interactions on subregional to global scales.
4. To examine secular air quality and climate changes to identify important current trends and to allow evaluation of model predictions and the testing of mechanistic hypotheses.

Major research efforts are needed to link anthropogenic changes in atmospheric chemistry, changes in climate, and the effects of the new climate on environmental systems. The National Science Foundation, National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, and the Department of Energy have traditionally been the major contributors to research in these aspects of the atmospheric sciences because of their support for development and analysis of general circulation models (GCMs). Their current and planned research programs are vital to continued progress and success in linking the atmospheric and ecological sciences. EPA, because of its existing expertise in meteorology and atmospheric chemistry, and its emphasis on environmental effects, will become an increasingly large contributor as well.

Research Strategy

Process models offer the potential for quantitative, deterministic understanding but suffer from known (and perhaps some unknown) deficiencies and limitations due to generalizing, parameterizing, or distorting physical and chemical relationships. Such deficiencies are unavoidable, so models must be tested for both sensitivity and accuracy. The scale of the model is chosen based upon the nature of the problems being studied. As a consequence, some processes are important factors on one scale of space and time but not on another. While the level of confidence in individual models varies widely from one use to another, it is clearly possible, as shown in this report, to produce early versions of atmospheric scenarios. These early efforts are clearly not entirely satisfactory, but they have provided useful directions for additional work. The approach from here on must be iterative in nature. Because models will not be able to provide all the needed information, analogue and statistical techniques must also be used.

Scenario Production

Scenario production in the future should be a three-step process involving the following: defining the needs of the users for scenarios; choosing, combining, and integrating the various methods of producing scenarios; running the various process and analogue models to produce sets of numbers, with guidance on their use; and distributing the scenarios to the research community. This will be an iterative process, producing new scenarios tailored to user needs and changing as models are developed or refined.

Because no one scenario will meet all the needs of ecological research groups concerned with different effects, a large number of scenarios tailored to the needs of each research group will have to be produced. For all the users, however, scenarios must address the frequency of occurrence of weather events; the significance of the environmental consequences; the degree of understanding connecting weather events and their consequences; and the knowledge of whether or not the proper atmospheric information can be provided (Robinson and Hill, 1987).

Scenario production teams will require statements of data needed from their clients. One potential problem is that many user needs for climatic data are poorly understood and defined, due in part to a lack of interaction between climatologists and other scientific disciplines.

General circulation models, as have been used for this report, are only partially suited for these purposes; regional and continental-scale simulations of precipitation, cloudiness, and soil moisture, and resolution of regional-climate detail on coarse computational grids, are all problems that need to be addressed. GCMs also do not include many atmospheric processes, such as chemistry and boundary layer meteorology. Since much of the necessary ecological research will be on the regional scale, GCM output must be augmented for scenario development. Promising approaches include using large-scale two-dimentional chemical models, regional air quality models, and analogue and statistical techniques. These various approaches need to be developed in a manner that will allow their inputs and boundary conditions to be taken, directly or indirectly, from GCMs.

Once regional models, large-scale models, and analogue techniques have been developed separately, they should be linked where desirable to produce the optimal tools for scenario production. One example might be to use analogue methods to modify the output of a GCM, then to use the output as input boundary conditions for regional climate and air quality models, then to use other methods to change their output from episodic to long-term means, and finally to use weather generators to find exceedances of air quality standards, drought probability, or other climatic indicators of interest in a small region.

The components mentioned above that make up atmospheric scenarios each need development programs. They are described in subsequent sections.

General Circulation Models

The major strength of general circulation models is that they are strictly process-oriented, and are thus capable of indicating the nature, magnitude, and causes of climate change. Not all processes can be treated in full detail; many must be incorporated through parameterization schemes that relate, either statistically or empirically, the processes to the output variable of concern. The major weakness of general circulation models is that their prediction capabilities are well characterized primarily for temperature and precipitation, which may not be sufficient variables for particular assessments. Furthermore, GCMs have difficulty predicting changes in regional climate. Therefore, techniques are needed to translate the significant portions of large-scale climate change available from these models into the smaller scales on which ecosystem effects usually take place. This spatial and temporal detail can be provided using either local models or historical analogue approaches.

Local Climate Models

Numerous process-oriented models have been developed on the scale of individual point-sources. While the basic model formulations are site-independent, the results depend on local conditions, and extrapolation is therefore difficult or impossible. Similarly, air quality models have characterized the urban boundary layer and considered detailed processes, but it is presently extremely difficult to produce a detailed model applicable to anything other than the specific location for which the parameterization was developed.

Mesoscale models are being developed, however, and the process orientation of mesoscale meteorological models suggests that they have the potential to be incorporated explicitly as subgrid scale processes within GCMs. One of the best developed of these models is MM-4, a numerical model designed to simulate or predict atmospheric circulation systems for short time periods on a spatial scale ranging from 20 to 2,000 km. MM-4 has been used to drive the Regional Acid Deposition Model (RADM) and can itself be driven by large-scale GCMs. It is not, however, a climate model and cannot presently be used as such.

One area where major improvements of local climate models can be expected is cloud processes. Clouds are strong players in potential nonlinear climate feedbacks, particularly on a subregional scale, as they influence radiative transfer, chemical reactions, transport of pollutants, and precipitation. Current models assume clouds exist when certain saturation or near-saturation conditions are met; however, real clouds form when supersaturation conditions exist relative to cloud condensation nuclei. There is a strong potential for feedback through changes in the ultraviolet part of solar radiation that affects the formation of cloud condensation nuclei. Before any local climate models can be built, linkages between atmospheric chemistry, cloud condensation nuclei, and the formation of all types of clouds must be understood.

Chemical Models

EPA is one of the national leaders in the construction, testing, and operation of regional-scale, three-dimensional meteorological and chemical transformation process models. These models have improved the understanding of the complex and nonlinear interactions of regional emissions, long-range transport, and free-radical gas phase and cloud (aqueous) phase chemistry of trace gases and aerosols. A natural extension of the present EPA mission is to expand these process-based tools to incorporate elements needed to address the effects of global climate change on the atmospheric environment.

Scale differences, both temporal and spatial, are a major impediment to simply merging modeling techniques between the climate model and regional air quality communities. Likewise, simply adding chemistry to a GCM is not presently feasible for the following reasons: (1) even the simplest chemistry model is presently very computer-intensive; and (2) due to the large spatial scales in GCMs, much of the critical concentration-dependent chemistry of the urban and industrial sources would be lost as the emissions were "smeared" over the whole grid cell volume. The manner in which emissions or sources affect global climate change must be understood through an understanding of how many of the trace gases are changed by urban and regional chemical systems. At the same time, changes in global climate will modify how the urban and regional chemistry and climate systems behave. Improvements in basic computer science and technology may help solve some of the strictly computational problems. However, the other issues require new science.

More developmental work is needed to improve our understanding of chemical mechanisms, especially for aromatic and biogenic species, before these mechanisms can reliably predict the fate of much of the mass of material emitted into the atmosphere by human sources.

Linking Available Models

Chemical and climate models have been developed largely in isolation from each other, so the process of linking them is not simple. In addition to technical problems associated with computer limitations, model structures, and basic formulation, a major problem area exists: merging the differing temporal and spatial scales used.

From the perspective of regional chemical modeling, the major research question must be: "How are the existing regional models, which are all episodic (a few days at most) in design and operation, and which need boundary conditions and externally specified weather streams, to be used to estimate the impacts of global climate change?" Clearly, we will need to incorporate new data sources, perhaps especially remote sensing of vegetation types, atmospheric chemical composition (Whitten, 1986), and climate into our modeling systems.

Model Evaluation

Performing model evaluations for models as complex as those discussed here requires a concerted group effort involving many scientists with both observational and theoretical skills and experience. A range of models will often be needed to understand these complex systems. To test such models, data will be needed that are associated with the operational aspects of the models (their ability to predict the items of interest) and the diagnosis of model performance (their ability to give the right answer for the right reason). Several problems exist in model evaluation, including observations taken at a different scale from the model's predictions; no available technology that can measure what the model calculates; model outputs that must be inferred from secondary data; models with incomplete descriptions of processes; biases of groups developing models; and different assumptions and scenarios used by different modeling groups. Accounting for these limitations will require field observations, laboratory data, or the use of simpler models emphasizing the processes being investigated.

Observational Analysis

Analyses are needed that provide information about the current state of the climate with emphasis on secular trends and their regional variations. These are needed for (1) the evaluation of process models, and (2) the production of scenarios for ecological and air quality risk assessments. There are many variables and time and space scales of interest. Two general needs, then, are to (1) develop methods of analysis capable of spanning several scales and variables, and (2) to develop priorities for particular variables and scales for specific purposes.

In general, the traditional physical elements of climate have been measured at numerous sites for many years. Other elements may have long records at a fairly restricted number of sites. In addition, a long tradition of paleoclimatic research using proxy data has provided a very long record for some regions and variables.

In contrast, the chemical variables of climate are routinely measured at few sites, and even those tend to have short record lengths. Few paleoclimatic investigations have considered chemical variables; however, some chemical data are becoming available from tree ring and ice core elemental analysis.

Quality control of observations of physical climate variables must be a major concern prior to any detailed climatological analysis. Many observations were originally obtained for operational weather forecasting purposes, so quality control was a relatively minor concern. There may have been changes in observational practices and equipment or in the surrounding area that may have created spurious climate changes. Adjusting climatic data sets is a difficult and highly skilled task; however, several data sets are available or are being developed (Karl et al., 1987).

The majority of quality-controlled data sets being developed emphasize factors needed for comparison with GCMs. However, for a particular scenario, these may not be the appropriate variables or time period. Quality controlled information on other variables, such as humidity or extreme winds, may be required. Another troublesome potential stems from the general failure to rigorously address the question of quality control of satellite-derived information.

Current Climate Statistics

The development of current climate statistics must be based on analytical techniques capable of addressing various time and space scales for different variables, requiring the use of appropriate statistical techniques combined with physical and chemical insight. The selection of appropriate summarizing statistics is complicated when the record is a continuously varying function on several time scales. Choosing stations representative of regions and scaling up from a series of points to a value representative of an entire area introduces further problems.

These questions have been addressed in the most depth on the global scale; however, apart from temperature, no physical climate variable has been assessed on a global scale (Mitchell, 1984; Jones et al., 1986). Chemical variables that have been assessed globally include gases such as CO_2 and CH_4. Regional variations, such as for tropospheric ozone concentrations, have also received considerable attention. Subglobal physical analyses have emphasized the continental scale. The regional scale has also been the one at which many of the long-term data sets have been developed (e.g., Karl et al., 1984; Lamb, 1987).

These analyses provide a wealth of detail about the current climate and its recent variability. However, identifiable deficiencies in the present state of knowledge remain, including the following: (1) no common statistical rationale to allow comparisons, and (2) an emphasis on surface phenomena without linkage to causal atmospheric phenomena, thus making linkage with process models or use in scenario development difficult.

A high priority is the development of a statistical framework for future analyses. The framework will need to allow flexibility when considering different variables in different regions, while allowing comparisons between analyses and providing a straightforward means of comparing results with process models.

Chemical elements of climate must also be studied to develop appropriate statistical methods of spatial and temporal analyses, development of techniques to link the various scales of interest, and development of techniques to relate the near-surface climate to the overall atmospheric processes causing them. A severe handicap for current work stems from the relative sparseness of the data.

Analogue Scenarios

Analogue scenarios are of two major types: those based on paleoclimatic data from proxy evidence (e.g., tree rings or lake sediments), and those based on the modern historical record. They have been developed primarily as complements to GCM results, to contribute to the understanding of how altered processes are reflected in different climates (Butzer, 1980; Williams and Wigley, 1983). Because of their connection to process models, currently available scenarios have emphasized the variables given by the models, mainly precipitation and temperature. As before, these may not be what the user of a scenario needs (Gates, 1985). A potential exists, however, for the development of very detailed analogue scenarios with specific user orientations.

A major research challenge is the development of new, scientifically valid techniques of analogue scenario production, the creation or assembly of appropriate data sets, the assessment of specific user needs, and the testing of the physical reality of scenarios produced. The analogue approach may provide the detail of a scenario, while process models provide the boundary conditions. However, the analysis of current trends in regional climate and the development of user-oriented analogue regional scenarios are likely to indicate the need for additional observational information.

RESEARCH INTEGRATION TOPICS

This report has treated each regional case study as a vehicle for illustrating potentially important environmental effects that may result from a change in the climate system. However, the capacity for truly integrating the research results of individual projects within each region has been limited. The purpose of integrating diverse aspects of science in a regional or subregional context is to ensure that scientific assessments derived from a research program have an internally consistent set of assumptions and relationships. Future regional case studies will need to address this problem, if regional and local concerns of environmental decisionmakers are to be reflected in scientific research and assessment.

Spatial Data Bases for Integration

Research in both the ecological and atmospheric sciences should produce early, qualitative estimates of continental and regional sensitivities based on the current understanding of environmental resources and the processes that control the responses of each ecosystem to climatic variability. The beginning stages of this process have clearly been taken in this report and will be added to, as noted earlier in this chapter.

However, once the early definitions of sensitivity have been made, there still remains the daunting task of determining the possible relationships between climatic variability and the underlying systems in the atmosphere and biosphere in a way that will enable future regional studies to best investigate sensitivities to climate change. This can be done only if current results and understandings are portrayed in a manner that will take into account both the actual results from modeling and experimental studies and their location on the landscape, i.e., in spatially structured data bases, analyzed with geographic information system (GIS) technologies.

Such spatially structured data bases can be used to produce maps, but their use goes far beyond traditional two-dimensional representations of geographic data. In particular, their main advantage may be the potential to track not only the results of experiments but also the uncertainty associated with both underlying measurements and with modeling algorithms. Thus, the spatially oriented data bases, if used in conjunction with geographic information system technology, can play both an assessment role and a quality assurance role.

Spatially oriented data bases therefore have three major purposes: (1) they provide a method of prioritizing research efforts within funding constraints; (2) they provide a ready-made method for validating projections, especially if temporal scales can be portrayed adequately; and (3) they provide a direct relationship to the regional, national, and international policy issues that are of most concern to environmental decisionmakers.

The production of such data bases should be thought of as the first stage in an ongoing iterative procedure. The initial state of the science will both qualitatively, and in some cases quantitatively, limit the utility of maps. However, the research priorities outlined here and pursued by other Federal and international organizations should enable us to improve the underlying information base and thereby improve the next estimates of resources' responses to climate change.

Scenario-Assessment Approach to Integration

Integrated modeling has been attempted in large-scale environmental issues many times before and may be useful for policy analysis or for heuristic purposes. However, the goal of a model adequate to simulate the dynamics of geophysical, chemical, and biological processes on global scales is clearly achievable only after decades of research (ESSC, 1988).

Given that achieving such a goal is at least several decades in the future, the question of integrating diverse aspects of science in global climate change and its potential effects still must be addressed now. A promising approach for integrating research results is to treat the entire cycle of information flow (Figure 18-5a) as a series of two-stage or three-stage processes (Figures 18-5b and 18-5c).

Within each two-stage process, research results should be treated as follows. The first part of the process will be the creation of a set of scenarios, where we define a scenario as a possible and plausible combination of variables derived from a set of internally consistent assumptions. The second part of the process will evaluate the range of changes that are potentially due to each scenario and will evaluate the sensitivity of the underlying systems to different aspects of the scenarios. Thus, scenarios of land-use change can be used to evaluate the possible changes in emissions; scenarios of emissions can be used to evaluate the possible changes in atmospheric composition; scenarios of atmospheric composition can be used to evaluate changes in climate; climatic scenarios can be used to evaluate the possible changes in ecosystems; and scenarios of ecosystem and land-use change can in turn be used to evaluate possible changes in emissions.

The use of a scenario-assessment approach as an integrating tool has several advantages. It will provide clear priorities for research on the sensitivities of important environmental processes in each scientific area. It maintains an holistic view of the problems of global change. It preserves the information on the uncertainty of model results and data, in both qualitative and potentially quantitative fashion. Each pair of

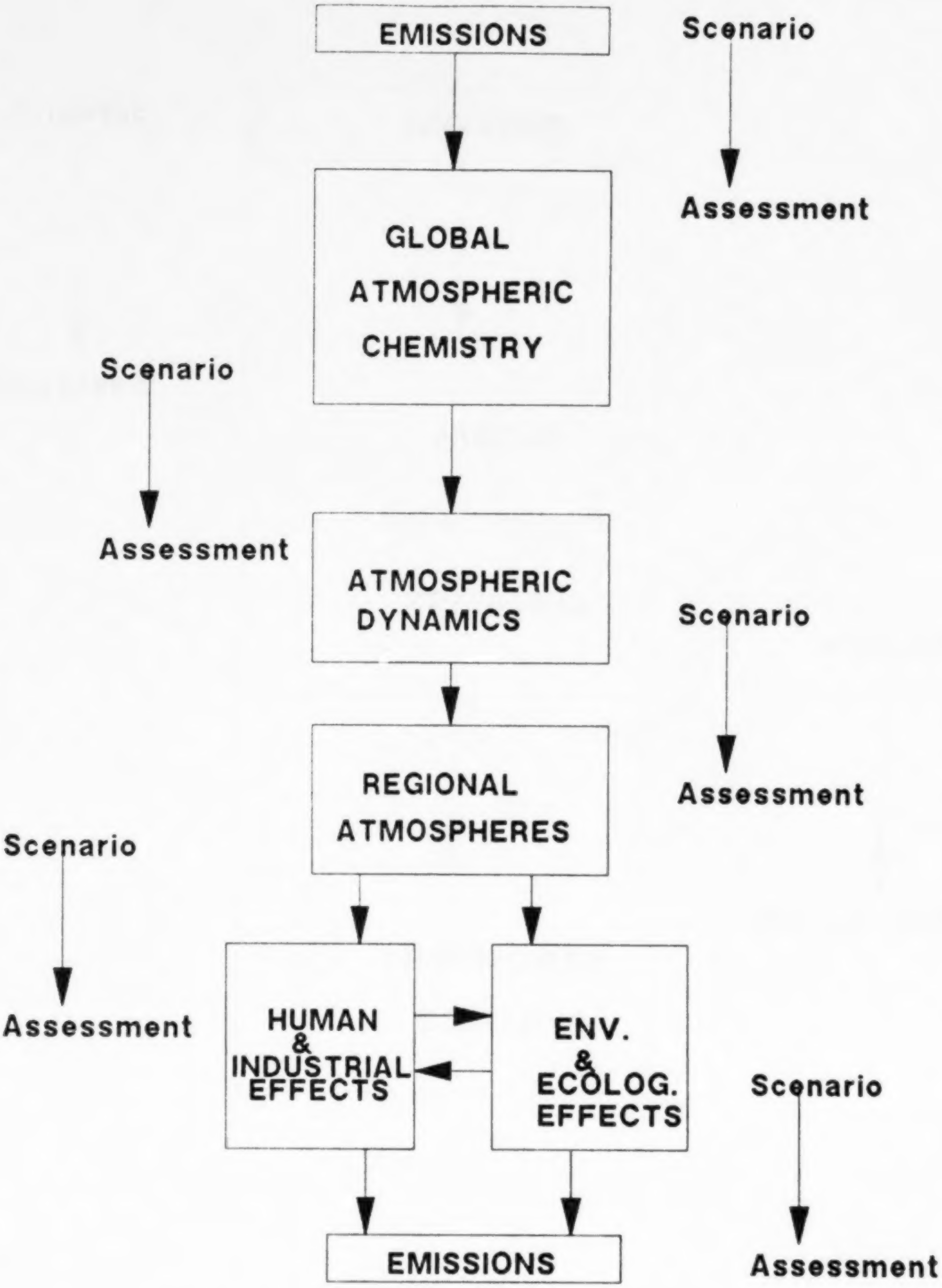
EMISSIONS
Scenario
Assessment
GLOBAL ATMOSPHERIC CHEMISTRY
Scenario
Assessment
ATMOSPHERIC DYNAMICS
Scenario
Assessment
REGIONAL ATMOSPHERES
Scenario
Assessment
HUMAN & INDUSTRIAL EFFECTS
ENV. & ECOLOG. EFFECTS
Scenario
Assessment
EMISSIONS

Figure 18-5a. Scenario approach to integration.

Source:

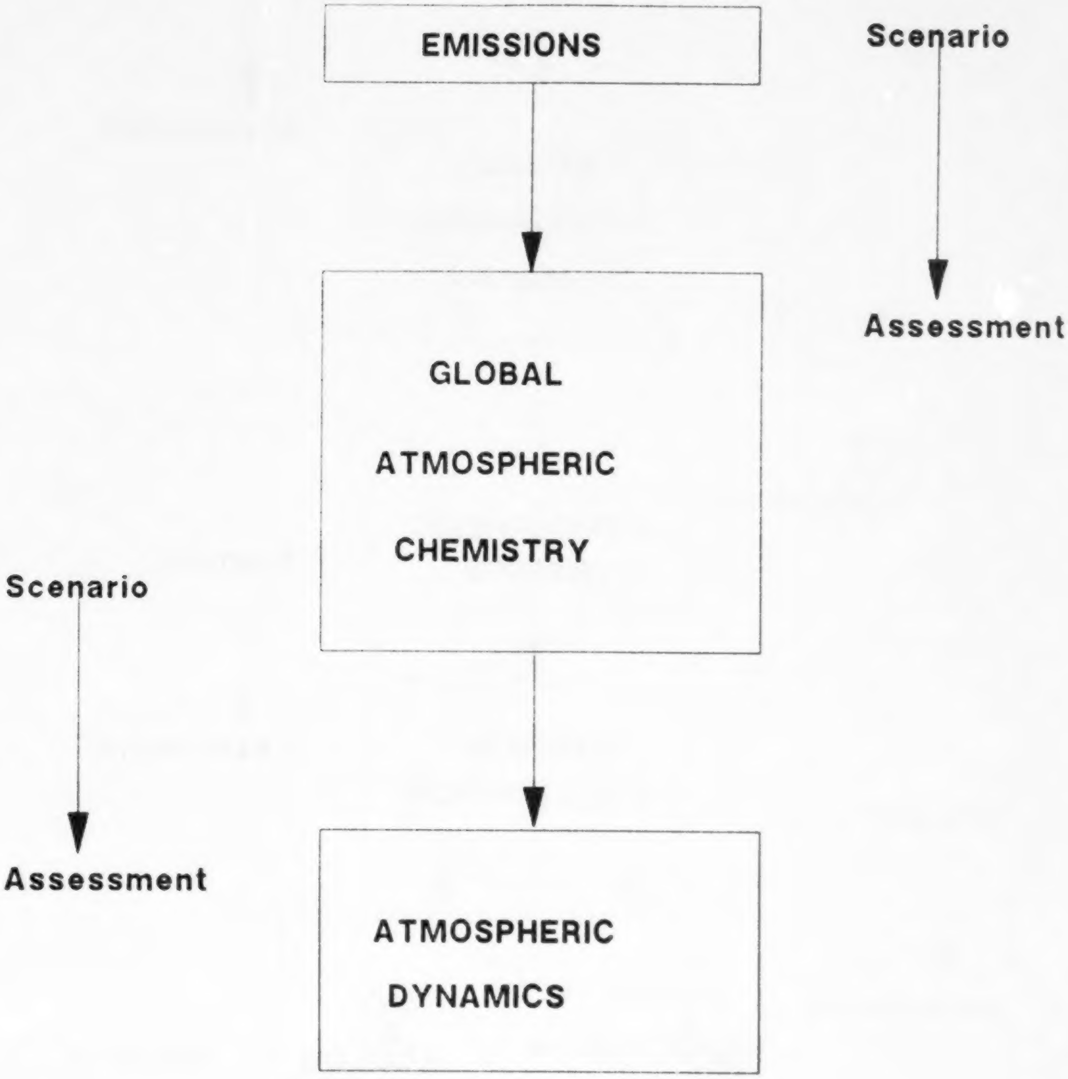
EMISSIONS
Scenario
Assessment
GLOBAL ATMOSPHERIC CHEMISTRY
Scenario
Assessment
ATMOSPHERIC DYNAMICS

Figure 18-5b. Scenario approach to integration.

Source:

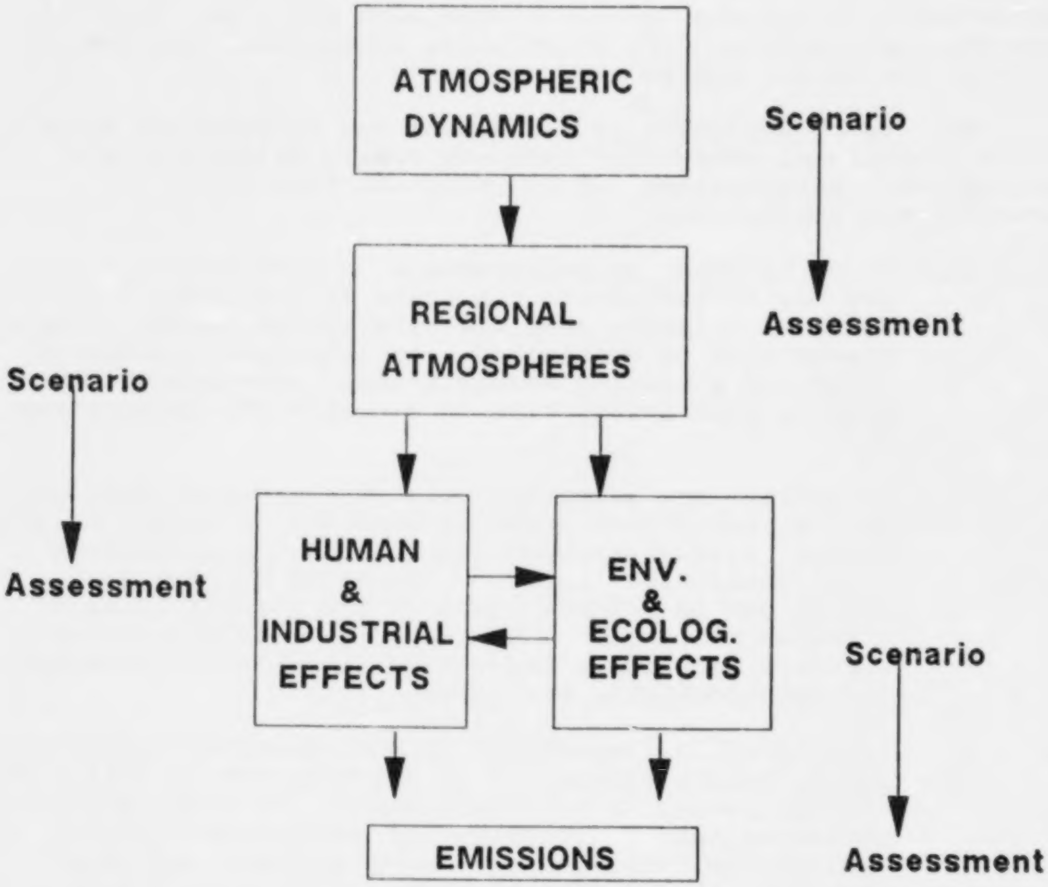
ATMOSPHERIC DYNAMICS
Scenario
Assessment
REGIONAL ATMOSPHERES
Scenario
Assessment
HUMAN & INDUSTRIAL EFFECTS
ENV. & ECOLOG. EFFECTS
Scenario
Assessment
EMISSIONS

Figure 18-5c. Scenario approach to integration.

Source:

scenario-response steps is explicitly decoupled from other pairs, while remaining consistent with them. Thus, this approach can indicate both ranges and sensitivities of responses in potentially verifiable fashion within each pair, but does not attempt the premature task of modeling uncertainty all the way through the global system.

The use of scenarios as assessment and integrative tools is not a traditional scientific approach toward prediction and validation. Nevertheless, it is important from three programmatic standpoints:

1. To be relevant to policymakers, a continued iterative process of evaluating the state of knowledge in the suite of sciences that are relevant to global climate change must be maintained. An iterative process of using and analyzing scenario-based assessments can provide such information in a usable and informative way.

2. To achieve the multidisciplinary syntheses needed to make scientific advances in problems of global climate change, evaluation must continue of the methods by which predictions are made, by which scenarios of change can be composed, and of the sensitivities of affected processes. The scenario-based assessment approach provides a ready-made integrating framework for such continual evaluation.

3. Because of the importance of this proposed research in public policy arenas, it is critical not to lose sight of what is and is not predictable. By distinguishing between a set of scenarios and actual verifiable predictions, the scenario-based approach can best illustrate the difference without becoming a morass of hedged bets.

CONCLUSION

In this chapter, we have attempted to lay out some of the most important strategic areas for scientific research in deriving an understanding of the environmental consequences of global atmospheric change. The recommendations have not been limited to the ecological sciences but have addressed the atmospheric sciences as well. Throughout, the focus has been on the research topics in the environmental sciences that will have the best chance of producing information that will be of use to environmental decisionmakers and policymakers.

In so doing, we have made suggestions that transcend research efforts that the Environmental Protection Agency will be able to pursue on its own. Our intent in doing so is to underscore the institutional requirements for cooperation among U.S. and international research organizations; close coordination with efforts such as the International Geosphere Biosphere Programme (NAS, 1986); and a continuing need for productive dialog between scientists and policy analysts. Our hope is that this report, and the research needs outlined here, can be seen as a beginning step in this direction.

Table 18-1: Major Research Topics From This Report

Research Area	Role of climate change
Water Resources	Analyses of impacts on small lakes and streams Better estimates of rainfall, runoff relationships, and regional runoff patterns Analyses of relationship between waterflow and water quality Analyses of changes in pesticide and fertilizer management practices on water quality
Agriculture	Interactive effects of carbon dioxide, climate change, air pollution, and ultraviolet-B (UV-B) radiation Development of drought-resistant varieties Field studies to validate crop yield models
Forest Ecosystems	Processes and rates of migration in critical regions Changes in land-use practices Interactive effects of climate change, air pollution, UV-B radiation, and carbon dioxide Ecosystem-level processes quantified for different landscape types Modeling and sampling strategies for regional effects
Human Health	Methods for assessing morbidity, mortality patterns Influence on disease vectors
Air Quality	Influence on urban, mesoscale air quality including acid deposition and zones
Fishery Resources	Impacts in sensitive estuaries Shifts of distributions in near-coastal species Ecological impact on freshwater species
General Circulation Models	Climate variability for 1xCO_2 and 2xCO_2 Simulations of climate on regional and local scales Simulations of major storms, hurricanes, and blocking events

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